2001-03

Investigation of the 25 January 2000 East Coast cyclogenesis

Schmeiser, Gregory J.

http://hdl.handle.net/10945/10847

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

INVESTIGATION OF THE 25 JANUARY 2000
EAST COAST CYCLOGENESIS

by

Gregory J. Schmeiser

March 2001

Thesis Advisor: Carlyle H. Wash
Second Reader: Patricia M. Pauley

Approved for public release; distribution is unlimited

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.			
1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** March 2001	**3. REPORT TYPE AND DATES COVERED** Master's Thesis	
4. TITLE AND SUBTITLE: Title (Mix case letters) Investigation of the 25 January 2000 East Coast Cyclogenesis			**5. FUNDING NUMBERS**
6. AUTHOR(S) Gregory J. Schmeiser			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for Public Release; Distribution is Unlimited			**12b. DISTRIBUTION CODE**

13. ABSTRACT *(maximum 200 words)*

On 25 January 2000, a rapidly developing cyclone tracked up the East Coast of the United States. Along with this system, 12 to 18 inches of snow fell on major cities from North Carolina to Washington DC. This snowstorm deserves special consideration because of the poor numerical and human forecasts it received.

The goal of this work is to analyze the performance of the Navy models, NOGAPS and COAMPS (West Atlantic) with the 25 January cyclogenesis event. Deficiencies with the model analyses and forecasts are identified and a diagnosis of critical model fields that led to these deficiencies is completed. Preliminary investigation of analyses and NOGAPS forecast runs with the new variational data assimilation system, NAVDAS, concludes the research.

The results of the research reveal that NOGAPS poorly forecast storm tracks while COAMPS showed more success. Both NOGAPS and COAMPS produced deficient short range upper-level height forecasts and had difficulty analyzing two prominent jet streaks. NOGAPS was not able to adequately analyze or forecast cold air damming and coastal frontogenesis, while COAMPS was more successful at resolving these features. COAMPS produced better precipitation forecasts than NOGAPS, but still showed deficiencies. Preliminary investigation of NOGAPS using NAVDAS shows promise.

14. SUBJECT TERMS Cyclogenesis, NOGAPS, COAMPS, NAVDAS			**15. NUMBER OF PAGES**
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

INVESTIGATION OF THE 25 JANUARY 2000 EAST COAST CYCLOGENESIS

Gregory J. Schmeiser
Lieutenant Commander, United States Navy
B.S., United States Naval Academy, 1990

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY AND PHYSICAL OCEANOGRAPHY

from the

NAVAL POSTGRADUATE SCHOOL
March 2001

Author: Gregory J. Schmeiser

Approved by: Carlyle H. Wash, Thesis Advisor

Patricia M. Pauley, Second Reader

Carlyle H. Wash, Chairman
Department of Meteorology

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

On 25 January 2000, a rapidly developing cyclone tracked up the East Coast of the United States. Along with this system, 12 to 18 inches of snow fell on major cities from North Carolina to Washington DC. This snowstorm deserves special consideration because of the poor numerical and human forecasts it received.

The goal of this work is to analyze the performance of the Navy models, NOGAPS and COAMPS (West Atlantic) with the 25 January cyclogenesis event. Deficiencies with the model analyses and forecasts are identified and a diagnosis of critical model fields that led to these deficiencies is completed. Preliminary investigation of analyses and NOGAPS forecast runs with the new variational data assimilation system, NAVDAS, concludes the research.

The results of the research reveal that NOGAPS poorly forecast storm tracks while COAMPS showed more success. Both NOGAPS and COAMPS produced deficient short range upper-level height forecasts and had difficulty analyzing two prominent jet streaks. NOGAPS was not able to adequately analyze or forecast cold air damming and coastal frontogenesis, while COAMPS was more successful at resolving these features. COAMPS produced better precipitation forecasts than NOGAPS, but still showed deficiencies. Preliminary investigation of NOGAPS using NAVDAS shows promise.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

I. INTRODUCTION 1

II. IMPORTANT COMPONENTS OF EAST COAST CYCLOGENESIS 5
- A. SEA-LEVEL CYCLONES 6
  - 1. Cyclone Development 6
  - 2. Track, Speed and Intensification 6
- B. THE ROLE OF COLD ANTICYCLONES 7
- C. MESOSCALE EFFECTS 8
- D. 850 MB LEVEL 8
- E. UPPER LEVEL DEVELOPMENT 9
  - 1. Jet Streak Dynamics 10
  - 2. Air Flow 12
- F. FRONTAL EVOLUTION 13

III. 25 JANUARY 2000 SNOWSTORM ANALYSIS 15
- A. OBSERVATIONAL DATA 15
  - 1. Sea Level Pressure 15
  - 2. Precipitation 16
- B. MODEL ANALYSES 17
- C. 24/00 ANALYSIS 17
  - 1. Upper Levels 17
  - 2. 850 mb and Surface 18
- D. 24/12 ANALYSIS 18
  - 1. Upper Levels 18
  - 2. 850 mb and Surface 19
- E. 25/00 ANALYSIS 20
  - 1. Upper Levels 20
  - 2. 850 mb and Surface 21
- F. 25/12 ANALYSIS 22
  - 1. Upper Levels 22
  - 2. 850 mb and Surface 23

IV. OPERATIONAL MODEL PERFORMANCE 35
- A. ACTUAL STORM TRACK 35
- B. NOGAPS AND COAMPS ANALYZED TRACK AND INTENSITY 35
- C. NOGAPS FORECAST TRACK AND INTENSITY ERRORS 36
- D. NOGAPS FORECAST PRECIPITATION ERRORS 38
- E. COAMPS FORECAST TRACK AND INTENSITY ERRORS 39
- F. COAMPS FORECAST PRECIPITATION ERRORS 40

V. UPPER-LEVEL AND COASTAL FRONT EVALUATION 53
- A. NOGAPS 500 MB FORECAST HEIGHT ERRORS 53
  - 1. 500 mb Height Forecasts for Valid Time 25/00 53

2. 500 mb Height Forecasts for Valid Time 25/12 53
B. COAMPS 500 MB FORECAST HEIGHT ERRORS 54
1. 500 mb Height Forecasts for Valid Time 25/00 54
2. 500 mb Height Forecasts for Valid Time 25/12 54
C. NOGAPS 250 MB ISOTACH ANALYSIS ERRORS 55
D. NOGAPS 250 MB FORECAST ISOTACH ERRORS 57
E. COAMPS 250 MB ISOTACH ANALYSIS ERRORS 58
F. COAMPS 250 MB FORECAST ISOTACH ERRORS 59
G. COASTAL FRONT 60
H. NOGAPS ANALYSIS OF THE COASTAL FRONT 61
I. NOGAPS FORECASTS OF THE COASTAL FRONT 62
J. COAMPS ANALYSIS OF THE COASTAL FRONT 62
K. COAMPS FORECAST OF THE COASTAL FRONT 63
L. SUMMARY 64

VI. NAVDAS 87
A. 250 MB ISOTACH ANALYSIS 87
B. FORECAST TRACK POSITION 88
C. 500 MB HEIGHT FORECASTS 89
D. PRECIPITATION FORECAST 89

VII. CONCLUSION AND RECOMMENDATION FOR FURTHER STUDY 97

APPENDIX. ADDITIONAL ANALYSES AND DATA 101

LIST OF REFERENCES 107

INITIAL DISTRIBUTION LIST 109

ACKNOWLEDGMENTS

The author would like to thank the following individuals for their support of this thesis:

Prof. Wash for your guidance and expertise as a thesis advisor.

Dr. Pauley for your direction as a second reader and your role with the NAVDAS runs.

Mr. Bob Creasey for your technical support and tireless effort with data collection and storage.

Dr. Ed Barker for providing the NAVDAS analyses and forecast runs.

Mr. Ron Picard for your help with archived COAMPS data.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

On 25 January 2000, a rapidly developing cyclone tracked up the East Coast of the United States. Associated with this system, 12 to 18 inches of snow fell on major cities from North Carolina to Washington DC. While it is not uncommon for several of these storms to occur in any given year, this snowstorm deserves special consideration because of the poor numerical and human forecasts.

Numerical model forecasts had difficulty handling the track of the storm, with most positioning it further east in the western Atlantic, not close to the coast. Twenty-four to 48 h model forecasts misplaced the position of the storm and made poor precipitation forecasts for the 25th. As a result of the poor guidance from the numerical models, local forecasters failed to predict the heavy snowfall until late in the evening on the 24th. In fact, the National Centers for Environmental Prediction (NCEP) overview of the storm points out that local forecasts issued at 4 PM on the 24th reported only a 40% chance of light snow in Washington. Only six hours later, heavy snow was falling in southern Virginia and moving north. The first indication many people had that a heavy snowfall was imminent was when they woke up on the 25th and saw the snow on the ground.

The Navy models, Navy Operational Global Atmospheric Prediction System (NOGAPS) (Bayler, et al., 1992) and Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS) (Hodur, 1997), also had difficulty predicting the storm track and

precipitation. The purpose of this research is to investigate the performance of the Navy models in predicting this storm.

Identifying performance error is the first part of the work. Determining why the model performance was poor is the second. Various model fields were investigated to determine where the errors occurred and how they impacted the track of the storm. It was found that upper-level processes and some low-level mesoscale effects were critical in the storm development. Upper-level height patterns, jet streaks, vorticity, and divergence were all very crucial to the development. Low-level features such as cold air damming and a coastal front also played a large role in the storm track. The ability of each model to analyze these fields, and in turn, forecast their development is discussed at length.

The timing of this study was fortunate to coincide with the testing phase of the Naval Research Laboratory Atmospheric Variational Data Assimilation System (NAVDAS) with the NOGAPS model (Daley and Barker, 2000). Analyses and forecasts were rerun using the NAVDAS data assimilation scheme and were available for this study. Comparisons were made to the operational NOGAPS, which uses the Multi-Variate Optimum Interpolation (MVOI) system (Barker, 1992). These findings and the effect of an advanced data assimilation system on the global model will be discussed in the final chapter.

This thesis begins with a description of important components of cyclogenesis, with an emphasis on features unique to the East Coast of the United States. This is followed in Chapter III by a synoptic description of the 25 January 2000 snowstorm. Navy operational model performance with respect to storm track, intensity, and

precipitation are discussed next in Chapter IV. Chapter V is a detailed description of the critical fields of the NOGAPS and COAMPS models, and is followed in Chapter VI with a discussion of the results from the NAVDAS runs. The thesis will end with the findings and conclusion in Chapter VII.

THIS PAGE INTENTIONALLY LEFT BLANK

II. IMPORTANT COMPONENTS OF EAST COAST CYCLOGENESIS

During the winter months of December, January and February, the East Coast of the United States experiences a high frequency of coastal cyclones. These storms often undergo explosive cyclogenesis and produce large amounts of liquid and frozen precipitation. Many factors, unique to the East Coast, are responsible for these systems, which are also called nor'easters. The topography of the eastern United States, particularly the Appalachian Mountains, the coastal plain and the coastline shape contribute to cyclogenetic conditions. Local effects such as cold air damming and coastal fronts create a strong low-level baroclinic zone. The concave shape of the Georgia/South Carolina/North Carolina coast, coupled with weak boundary layer static stability near the Gulf Stream, typically foster storm tracks very close to the coast (Bosart, 1975). The proximity of major cities and ocean ports on the east coast makes forecasting these events and associated precipitation crucial.

In addition to the low-level baroclinic zone, upper-level support is important for surface cyclogenesis. Ahrens (1991) describes the influence of upper-level long wave troughs on mid-latitude cyclones. At any given time, four to six long waves encircle the Northern Hemisphere. Due to the upper-level flow over the Rockies, a long wave trough is often in place over the East Coast of the United States. Unlike short waves, long waves remain stationary or move very slowly. As short waves propagate through the long waves, the short wave trough usually deepens as it approaches the long wave trough if baroclinic conditions are present. The presence of the stationary long wave trough over

the East Coast and the propagating short waves contribute to cyclogenetic conditions in this area.

A. SEA-LEVEL CYCLONES

1. Cyclone Development

Kocin and Uccellini (1990), in their study of significant East Coast snowstorms, define two types of East Coast cyclone formation, Type A and Type B. Type A describes a primary development. These cyclones typically form along the Gulf Coast and cross the Florida peninsula into the Atlantic Ocean. Once in the Atlantic, they track north along the East Coast. In many cases, the Type A cyclone experiences a center jump, that is, a low that redevelops suddenly along its primary path, or simply appears to jump forward. This commonly occurs along the Carolina coast. The 25 January 2000 snowstorm was a Type A development.

Type B development is a type of secondary redevelopment. In this case, a primary low originates in the southern Plains states and propagates toward the Ohio Valley. The warm front of this primary low extends into the western Atlantic, where a secondary low forms offshore and undergoes cyclogenesis. The primary low typically fills while the secondary low develops.

2. Track, Speed and Intensification

Historically, propagation speeds and minimum pressures vary from storm to storm. Each low typically experiences a rapid deepening period of 6 to 27 h. Kocin and Uccellini (1990) define rapid development as a Mean Sea Level pressure (MSLP) deepening rate exceeding -3 mb/3 h. The heaviest snowfall often coincides with the rapid deepening period.

The location of a heavy snow band is very much influenced by the track and propagation speed. Snow bands are normally 200 to 500 km wide and up to 500 km long. They are oriented from the southwest to the northeast and lie 100 to 300 km to the left and parallel of the cyclone path. Slower storms affect an area longer, and therefore are capable of producing more snow locally. Additionally, since heavy snowfall periods are closely related to rapid deepening periods, the accurate prediction of the rapid deepening period, track, and propagation speed is necessary for reliable precipitation forecasts. (Kocin and Uccellini, 1990)

B. THE ROLE OF COLD ANTICYCLONES

Cold air is normally supplied to the coastal plain when an anticyclone is in place over southern Canada. This anticyclone is not stationary, and will track either east toward New England or south into the Plains states. Ridging from the anticyclone will affect the northeast United States by driving cold air south between the Appalachian Mountains and the coast. This is known as cold air damming and is described in the next section. The cold air has a path mainly over land, so it is not influenced or modified by oceanic moisture or heat fluxes.

If the anticyclone drifts too far east, the circulation will pass over the ocean, and the flow will be modified by oceanic boundary layer fluxes. This condition strongly influences the type of precipitation that falls. In these cases, the precipitation along the immediate coast is mainly rain, with the snow band placed further to the west. (Kocin and Uccellini, 1990)

C. MESOSCALE EFFECTS

Cold air damming is a unique feature of the east coast regions. With an anticyclone in place over southern Canada, cold air is wedged between the coast and the Appalachian Mountains. The length scale of the coastal plain is insufficient for this cold air outbreak to geostrophically adjust. As a result, cold air damming will have highly ageostrophic, northerly winds. Cold air damming is evidenced by colder than average temperatures and by an inverted sea level pressure ridge between the mountains and the coast. These cold temperatures help to maintain a strong low-level thermal gradient along the coast. For more details see Forbes et al. (1987) or Bell and Bosart (1988).

Converging winds along the coast lead to coastal front formation. As a result of cold air damming, the overland surface winds are mainly from the north. These winds have little modification from the ocean. However, as the cold anticyclone moves to the east, a part of the low-level flow will favor synoptic forcing and have more of a northeast component. These winds will be influenced by the oceanic boundary layer moisture and heat fluxes. These two flows are convergent along the East Coast and will create a strong low-level baroclinic zone along the coast. The coastal front provides baroclinicity, convergence, and low-level vorticity to aid cyclogenesis. (Bosart, 1975)

D. 850 MB LEVEL

As the surface low is developing, an 850 mb low will typically develop slightly to the west of the surface feature. The position of the 0° C isotherm is commonly used as the rain/snow line. Cold air advection to the west of the 850 mb low and warm air advection to the east will cause a distinct S-shaped isotherm pattern, which is normally centered on the 850 mb low.

Two distinct low level jets (LLJ) occur at 850 mb, and are useful in identifying temperature advections. The cold air advection to the west of the 850 mb low occurs in association with an LLJ. This LLJ forms prior to or during cyclogenesis and will have north or northwest winds of 15 m/s or more. Flow is perpendicular to the isotherms and will advect the 0° isotherm to the south. A warm LLJ to the east and southeast of the 850 mb low will occur at the onset of cyclogenesis. South or southeast flow of 25 to 35 m/s is common. The warm LLJ enhances temperature and moisture advections into the snowfall regions. (Kocin and Uccellini, 1990)

E. UPPER LEVEL DEVELOPMENT

As with any mid-latitude cyclogenesis, upper-level divergence must interact with the low-level baroclinic zone for the system to develop. Since divergence is impractical to measure, it is often inferred from vorticity and vorticity advections. Conceptual models are useful in visualizing divergent regions, for example, the divergent region between a trough and a downstream ridge due to the along-stream ageostrophic wind component.

Temperature advections influence the amplitude of an upper-level wave. Cold air advection below a trough and warm air advection below a ridge will increase the amplitude. Latent heating below a ridge must also be considered. Increased wave amplitude creates larger vorticity gradients and is related to greater divergence aloft.

An amplifying ridge also has a large impact on wavelength and tilt. As the ridge builds, the half-wavelength typically decreases. The wavelength decreases because as the ridge is amplifying, its propagation speed is slowing. The trough approaches the ridge and the half-wavelength decreases. This decrease in wavelength is accompanied by a

shift in the tilt from positive (northeast to southwest) to negative (northwest to southeast). As the tilt becomes negative, the downstream heights become diffluent.

While these features describe most cyclogenesis events, their proximity to the East Coast can allow a majority of the latent heating to occur over the western Atlantic, which causes the amplifying ridge to be over the East Coast or just offshore. As the trough propagates to the east, the increase in amplitude, decrease in wavelength and shift in tilt are all affecting the East Coast and coastal waters. The diffluent region is then effectively over the surface baroclinic zone of the coastal front.

While the East Coast of the United States is influenced by the trough/ridge system, the cold anticyclone over southern Canada is also supported aloft. This anticyclone often underlies a convergent upper-level region and subsidence. The anticyclone is able to continue providing cold air for damming episodes and maintains the low-level baroclinic zone along the East Coast. (Kocin and Uccellini, 1990)

1. Jet Streak Dynamics

The ageostrophic transverse circulation of jet streaks can also play a large role in cyclogenesis. The entrance region has a thermally direct transverse circulation, with the right entrance region divergent and the left entrance region convergent. The exit region is thermally indirect, with the left exit region divergent and the right exit region convergent.

During East Coast cyclogenesis, the coastal waters are often under the influence of two separate jet streaks. One jet streak is over southeastern Canada or New England and is associated with the confluent flow that supports the cold anticyclone. The second streak enters the base of the trough along the southeast coast of the United States. The

interaction of these two jet streaks can create an enhanced area of upper-level divergence and upward motion that supports rapid deepening of a surface low. This interaction would occur when the upward motion in the right entrance region of the northern jet streak coincides with the left exit region of the southern jet streak as shown in Fig. 2.1. In their study of 20 major East Coast snowstorms, Kocin and Uccellini (1990) found that upper-level jet streaks were present at the base of the trough during cyclogenesis in all 20 cases. Seventeen cases had a jet streak across the northeastern United States or southeastern Canada.

In rare cases, the cold anticyclone over southern Canada and a northern jet streak are not present. Enhanced vertical motion may still be possible if a jet streak exists in the downstream ridge of the amplifying wave. This occurs when the upper-level trough takes on a negative tilt over the East Coast. A southerly or southwesterly jet streak may form over the coastal plain such that the right entrance region of this jet is positioned over the coast or coastal waters. Interaction with the left exit region of the jet streak entering the base of the trough is possible due to the negative tilt of the trough. As a result, a region of enhanced upward motion may exist along the East Coast.

When considering jet streak dynamics, the intensity of the along-flow wind shear is usually more important than the maximum wind speed. A greater horizontal wind shear will create larger vorticity advections in the entrance and exit regions, which imply stronger divergent and convergent areas. Also of high importance is the size of the acceleration region of the jet streak. Large wind acceleration over a short distance is highly ageostrophic and produces a large magnitude of divergence.

2. Air Flow

The warm conveyor belt (WCB) originates in southerly flow near the surface in the warm sector, ahead of the cold front, and ascends as it moves north. The flow turns anticyclonically and joins the upper-level westerly flow. The WCB forms the "tail" of the comma cloud and is not a heavy snow region. (Carlson, 1991)

The cold conveyor belt (CCB) originates at the surface as easterly flow north and east of the warm front. In the case of East Coast cyclogenesis, this low-level flow is generally influenced by the cold anticyclone to the north. It ascends sharply up the isentropic surface created by the upper-level trough/ridge system. The CCB may split into two flows. In the mid-troposphere, some air will turn cyclonically around the surface low. The remaining flow will continue its ascent and turn anticyclonically to a westerly outflow. The CCB forms the "head" of the comma cloud and is an area of potentially heavy precipitation. At the lower levels, moisture is gained from oceanic boundary layer fluxes. As seen in Figure 2.2, the CCB partially underlies the WCB. In this region the CCB gains moisture when precipitation from the WCB falls on to it. The CCB produces large amounts of precipitation as this moisture rich air makes its sharp ascent. (Kocin and Uccellini, 1990)

The dry tongue is air of stratospheric origin and is associated with a tropopause fold. Other common names are the dry intrusion or dry air stream. Tropopause folding brings high values of potential vorticity to the middle and lower troposphere. These stratospheric intrusions are conducive to cyclogenesis. Carlson (1991) shows the conversion of high potential vorticity values to high absolute vorticity values can occur through column stretching with vertical motions along frontal surfaces.

The dry tongue splits into two branches. One descends behind the cold front. The other dips down near the cyclone center and then ascends to join the westerly outflow parallel to the CCB and WCB. The dry air intrusion gives the comma head its shape. (Kocin and Uccellini, 1990)

F. FRONTAL EVOLUTION

As the system approaches occlusion, the cold front/warm front structure may fracture. The cold front is then able to propagate to the east along the warm front. Shapiro and Keyser (1990) describe this occurrence as a "T-bone" structure.

In place of an occluded front structure, frontogenesis may occur along the western extent of the warm front. This "bent back" warm front will extend to the west of the surface low. The "bent back warm front" gets its name because this feature has more characteristics of a warm front than an occluded front.

The bent back warm front is a low-level, highly baroclinic region. As it extends to the west, it may wrap around the surface low and create a warm seclusion at the cyclone center. It is a narrow and shallow feature and slopes up and to the west. Typically it overlies a northerly low-level jet with maximum wind speeds of 35 to 50 m/s, and winds will be southerly above it (Shapiro and Keyser, 1990). This is a localized feature that may help explain a cloud band that bends back around the low. A narrow band of heavy precipitation falling to the west of the surface low often accompanies this cloud band.

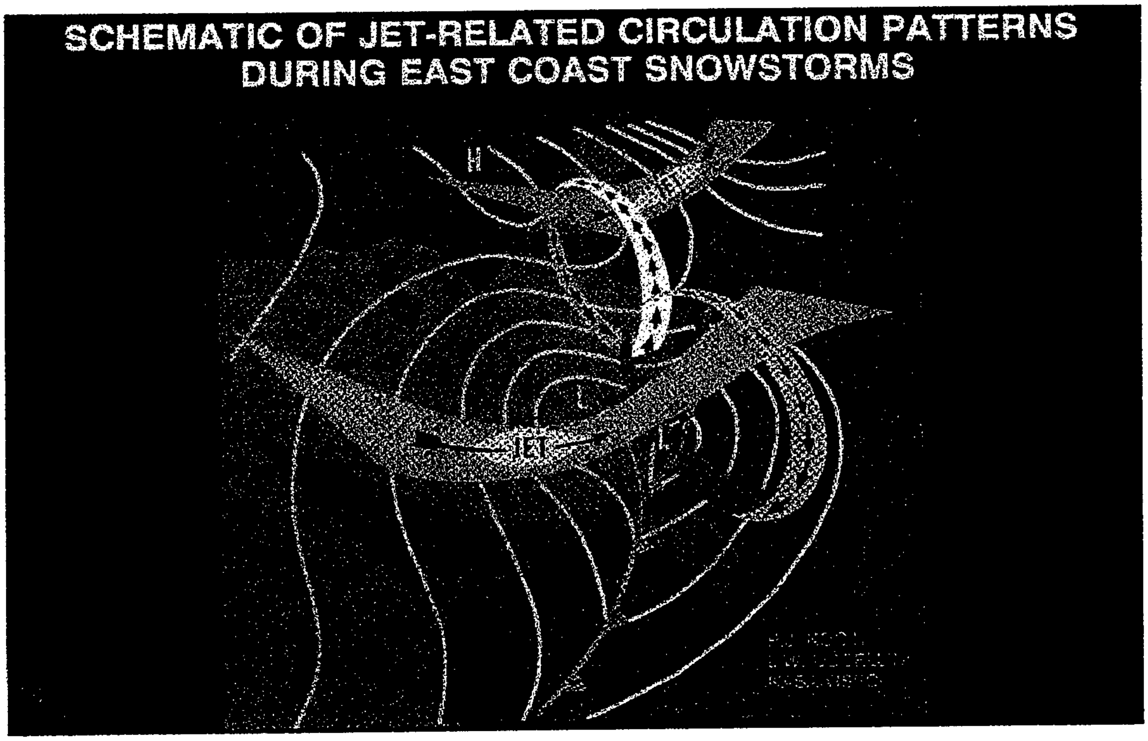


Figure 2.1. Jet-Related Circulation Patterns. (from: Kocin and Uccellini, 1990)

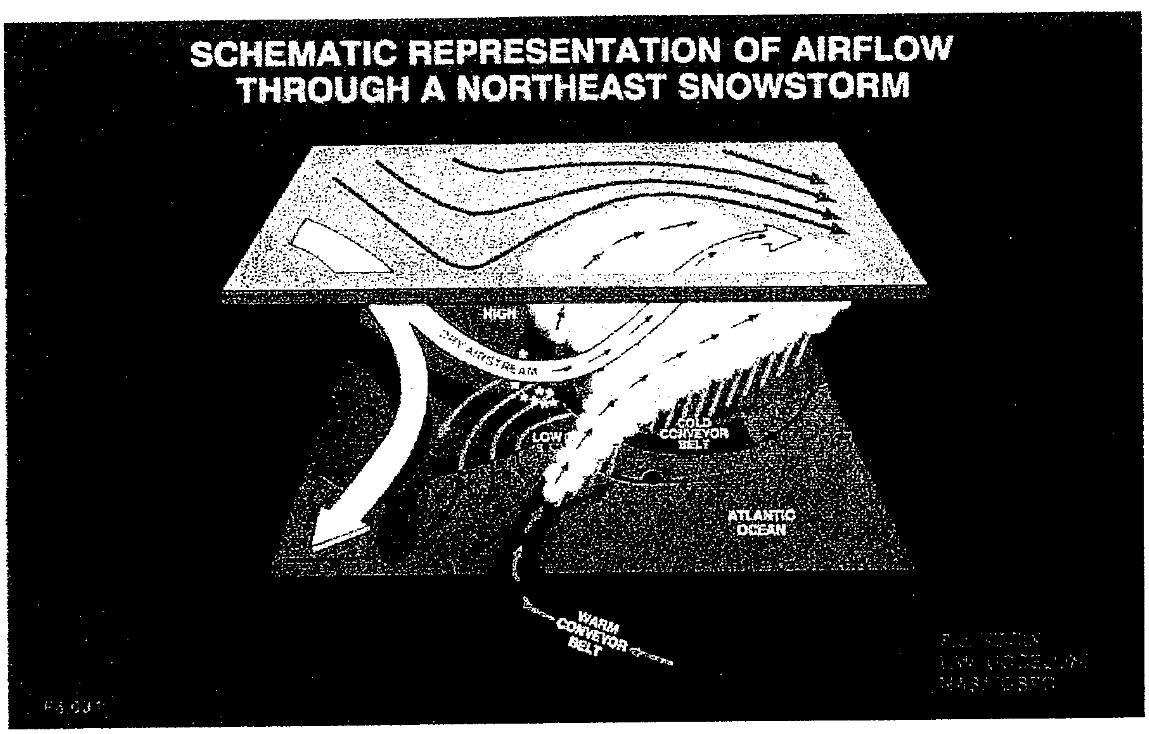


Figure 2.2. Airflow Through a Northeast Snowstorm. (from: Kocin and Uccellini, 1990)

III. 25 JANUARY 2000 SNOWSTORM ANALYSIS

The purpose of this chapter is to describe the evolution of the 25 January 2000 cyclogenesis event. First in Section A, observed data are used to document sea level pressure and observed snowfall amounts. Following sections will use NOGAPS analysis fields to describe the vertical structure of the storm.

A. OBSERVATIONAL DATA

1. Sea Level Pressure

Three sources are used to describe the development of this cyclone: (1) a surface hand analysis (Appendix, Fig. A1 through A7) from the State College, PA, National Weather Service (NWS) Forecast Office, (2) moored buoy and Coastal-Marine Automated Network (C-MAN) station data from the National Buoy Data Center, and (3) NOGAPS and COAMPS (West Atlantic) sea level pressure analyses. The model analyses were necessary for continuity of time periods before 25/00.

Rapid cyclogenesis began at 24/12 when the incipient low (1007 mb) moved over the Florida peninsula (Fig. 3.9). By 25/00 the central pressure dropped to 994 mb as the cyclone transited off the coast of South Carolina (Fig. A1). The system further deepened 4 mb to 990 mb by 25/03 (Fig. A2) and another 10 mb to 980 mb over the next three hours (25/06), at which time the low was positioned over Cape Hatteras, NC (Fig. A3). Although no change in central pressure was analyzed between 25/06 and 25/12 (Fig. A4), deepening continued until 25/18 with a minimum central pressure of 976 mb (Fig. A5). The low continued to track up the east coast (Fig. A6 and A7) while it slowly filled to

990 mb when it reached southern Maine at 26/12 (not shown). More details on the storm track and intensity are found in Chapter IV.

2. Precipitation

National Weather Service hand-analyzed accumulated snowfall for 24 and 25 January (Fig. A8) shows a narrow band of heavy snow fell in central North Carolina, eastern Virginia and western Maryland. Four cities were chosen to describe this band: Raleigh, NC (RDU); Richmond, VA (RIC); Washington DC (DCA) and Baltimore, MD (BWI). Raleigh-Durham airport set a new snowfall record with 20.3 inches of snow. Fifteen inches fell between 25/05Z (midnight local time) and 25/11Z. Richmond recorded 10.7 inches of snow at the airport and 12.5 inches in the city. All surrounding counties received nine to fifteen inches of snow, with the heavy snow period from 25/07Z to 25/19Z. Washington DC and Baltimore were affected similarly. Ronald Reagan International Airport (DCA) received 12 inches of snow, while Baltimore measured 17 inches in the city. In both cities, heavy snow began around 25/09Z with light to heavy periods over the next twelve to fifteen hours.

The heavy snow periods determined from airport observations were compared to digital radar products. Radar data for the period (Fig. A9 through A22) correlates well with both infrared (IR) imagery and the airport observations as the snowfall region tracks from south to north. The heavy snow band coincides with a bent-back cloud feature on the satellite imagery. Numerical models provided poor forecasts of this heavy snowfall area.

B. MODEL ANALYSES

The following description of the cyclogenesis event is based on operational NOGAPS analyses every 12 h from 00Z 24 January to 12Z 25 January, referenced as 24/00, 24/12, 25/00 and 25/12. These analyses are from the Navy's Multi-Variate Optimum Interpolation (MVOI) system. As with any model, the analysis fields are not a perfect representation of the true atmosphere. Even so, the NOGAPS analyses describe the general synoptic features of the storm well. There are, however, mesoscale features that are not resolved well in the NOGAPS analyses. These discrepancies will be addressed in following chapters.

C. 24/00 ANALYSIS

1. Upper Levels

A positive tilted short wave trough is found initially over the central United States (Fig. 3.1). The trough axis extends from Michigan to Oklahoma with a vorticity max extending the length of the trough axis. Downstream, a small short wave ridge is located over the western Atlantic Ocean and Canadian maritime provinces.

At 250 mb, two impressive jet streaks dominate the flow (Fig. 3.2). A 130 kt jet streak is entering the base of the short wave trough, while a separate polar jet streak is found along the East Coast with a 140 kt maximum to the east of Maine. The East Coast jet streak is positioned such that the anticyclonic shear side is affecting the coast and coastal waters. In particular, the right entrance region is located over the North Carolina and South Carolina coasts. The right exit region overlies a high pressure system in the west Atlantic. The 250 mb divergence field (not shown) indicates divergence overlying an extensive cloudy region along the East Coast, from Florida to New England. Close

inspection of the upper levels indicates the western jet stream wind maximum extending to 500 mb as it enters the base of the trough.

2. 850 mb and Surface

A trough is present at 850 mb centered over Mississippi and Alabama (Fig. 3.3), with significant cold air advection occurring west of the trough. Thirty to 35 kt winds and warm air advection are found just off shore along the Atlantic Coast. The 0° isotherm, an indicator of the rain/snow line, is found over the Virginia/North Carolina border.

At sea level, an inverted trough is located off the East Coast with a weak 1012 mb low to the north (Fig. 3.4). This low center will be referred to as "the preceding low" and is 450 km to the east of Norfolk, VA. Of particular interest is that there is no cold anticyclone over southeastern Canada or New England. A 1030 mb high pressure center is in place in the western Atlantic with a ridge extending back into Nova Scotia, and a 1027 mb high pressure system is located over the central United States. Cold air damming, even in the global analysis, is evident from an inverted ridge extending from Maine to Pennsylvania. The incipient cyclone is forming within a broad low center along the Gulf Coast.

D. 24/12 ANALYSIS

1. Upper Levels

After 12 h, the short wave trough begins to shear into two separate features. The northern part is simply propagating, not deepening, and shearing off from the southern part. The southern part over Alabama and Tennessee has deepened 90 to 120 meters (Fig. 3.5). The vorticity maximum identifies the base of the trough and indicates that the trough tilt is becoming north-south. The water vapor satellite image (Fig. 3.6) shows a

baroclinic leaf between the trough and the building downstream ridge along the East Coast. The radar composite from 24/09 to 24/15 (Fig. A12 through A14) verifies that moderate to heavy precipitation accompanies this leaf structure through Georgia and the Florida panhandle. In addition, the water vapor imagery shows a prominent dry slot entering the base of the trough. High values of potential vorticity for the 500 to 200 mb layer coincide with the dry air and show the presence of a tropopause fold.

The downstream 250 mb jet streak has become more aligned with the coast with little curvature. The 130 kt core of the jet streak is north of Virginia so that the acceleration region of the jet streak is over the North Carolina and Virginia coasts (Fig. 3.7). This places the divergent right entrance region over the Carolina and Georgia coast.

The western jet streak continues to propagate through the base of the short wave trough. The wind speeds have not increased over the last twelve hours, but the jet streak is longer and narrower. The isotachs at 500 mb (not shown) indicate the jet streak is in the base of the trough and correlates with the dry intrusion.

2. 850 mb and Surface

By this time, the 850 mb trough has propagated into the southeastern states. Northerly 25 kt winds from Missouri to the Florida panhandle are associated with cold air advection west and northwest of the developing surface cyclone. Warm air advection to the east of the trough is supported by 30 to 50 kt southwesterly winds. The intensifying temperature advections have strengthened and shifted the frontal zone from a nearly zonal pattern to a southwest to northeast orientation across the coast (Fig. 3.8).

The preceding surface low has deepened to 1002 mb and moved to 375 km east of Cape Cod. A closed 1008 mb isobar over north and central Florida marks the surface

cyclogenesis location of the snowstorm cyclone. It is connected to the preceding low by an inverted trough (Fig. 3.9). Cold air damming is still evident by an inverted ridge over the coastal plain. The anticyclone over the central United States continues to move southeastward.

E. 25/00 ANALYSIS

1. Upper Levels

By 25/00, the short wave trough has separated into two short waves. The northern one has propagated to Maine and is identified by a small vorticity max just west of the preceding low (Fig. 3.10). The southern part has formed a cutoff low over the South Carolina/Georgia border and is supporting the surface cyclogenesis. The vorticity max associated with the cut off low indicates a neutral to slightly negative tilt. Because of the change in tilt, a diffluent flow is developing downstream over the North Carolina and Virginia coasts. Also the downstream ridge is strengthening over the North Carolina, Virginia, and New Jersey coasts. As a result, the half-wavelength of the trough/ridge system has decreased and its amplitude has increased over the past twelve hours.

The water vapor imagery (Fig. 3.11) shows a very prominent dry slot to the west and south of the 500 mb cutoff low. The dry air is present poleward of the upstream jet and penetrates the 500 mb cutoff. High values of potential vorticity indicate this dry air is of stratospheric origin.

The eastern 250 mb jet streak axis continues to be positioned over the coastal waters from North Carolina through New England such that the right entrance region of the jet maintains support for upward motion over the surface low and westward to the North Carolina coast. (Fig. 3.12). The 250 mb divergence field (not shown) further

indicates that the associated broad area of divergence matches the cloudy region of the developing cyclone. However, close inspection of sounding data suggests that NOGAPS has analyzed the entrance region to the 250 mb jet streak too far to the east. Observed 250 mb winds show that the jet streak should be further inland, not just offshore, with the right entrance region over the coastal waters of North Carolina. This discrepancy will be discussed in Chapter V.

The upstream or southern 250 mb jet streak is positioned such that the left exit region overlies Alabama, Georgia and Florida. However, this area is coincident with upper-level convergence upstream of the trough, which supports downward motion. Satellite imagery shows these three states to be relatively clear, which indicates the strength of the convergence. Therefore, the upper-level divergence downstream of the trough, combined with the right entrance region of the downstream jet streak, together yield the strong 250 mb divergence max over the coastal waters of Georgia, South Carolina and North Carolina at this time.

2. 850 mb and Surface

An 850 mb cyclone has intensified and overlies the South Carolina coast, where the heights have dropped 60 to 90 meters (Fig. 3.13). There are strong thermal advections associated with the cyclone. Thirty to 40 kt winds west and southwest of the closed low indicate an increase in the cold air advection affecting the Gulf Coast and the northern Gulf of Mexico. These temperature advections have created an S-shape isotherm pattern centered on the 850 low. The 0° isotherm is slightly northwest of the low center and extends into Florida and northward up the South Carolina coast into eastern North Carolina and Virginia.

Vigorous surface cyclogenesis is underway as well (Fig. 3.14). The low is now off the coast of South Carolina and has deepened to 994 mb. The preceding low is 1003 mb and has moved to the northeast, where it is just downstream of the weak northern 500 mb short wave trough. The frontal structure of the cyclone is interconnected with frontal structure of the preceding low. The warm front extends to the north and connects with the cold front of the preceding low. The cold front extends to the south through the Bahamas and Cuba.

F. 25/12 ANALYSIS

1. Upper Levels

By 25/12, the 500 mb low has deepened 60 meters and has moved northeastward along the East Coast (Fig. 3.15). It has a negative tilt and is nearly vertically stacked with the surface low. The downstream ridge continues to build over New England. As a result, the wavelength has continued to decrease and the amplitude has continued to increase. The diffluent height pattern downstream of the cutoff low is more pronounced due to this increased negative tilt and curvature.

At 250 mb, the eastern 120 kt jet streak remains parallel to the coast (Fig. 3.16). The surface low is on the cyclonic shear side of the jet streak with the left exit region overlying a future position of the low. Because of the offshore position of the jet streak, there is no sounding data to confirm its location. However, sounding data from East Coast stations do suggest that the model analyses again may have positioned the entrance region to this jet streak too far to the east as it did with the 25/00 analysis (see Chapter V).

Two separate jet streaks can be identified in the comma shaped isotach field. One is oriented east-west and the other is north-south. The left exit region of the north-south jet streak is interacting with the right entrance region of the zonal jet streak. This interaction is producing enhanced vertical motion and corresponds with a 250 mb divergence area. This region overlies the bent back feature in the IR imagery.

2. 850 mb and Surface

The 850 mb low is moving northward along the East Coast with the surface feature (Fig. 3.17). Cold air advection supported by 25 to 30 kt winds is occurring to the west and south of the 850 low. The 0° isotherm is nearly centered on the low and extends into Georgia. Forty to 65 kt winds ahead of the cold front are advecting warm temperatures from the southeast cyclonically to the northwest around the low.

Active cyclogenesis has continued over the previous twelve hours (Fig. 3.18). The low has deepened to 979 mb and is offshore of Cape Hatteras. The frontal structure has fractured and exhibits the T-bone pattern described by Shapiro and Keyser (1990). The bent back warm front is clearly seen in satellite imagery, with a cloud band extending backwards from New England south into central North Carolina and Virginia. The lowest central pressure (976 mb) occurs six hours later at 25/18, when the system becomes vertical and begins filling.

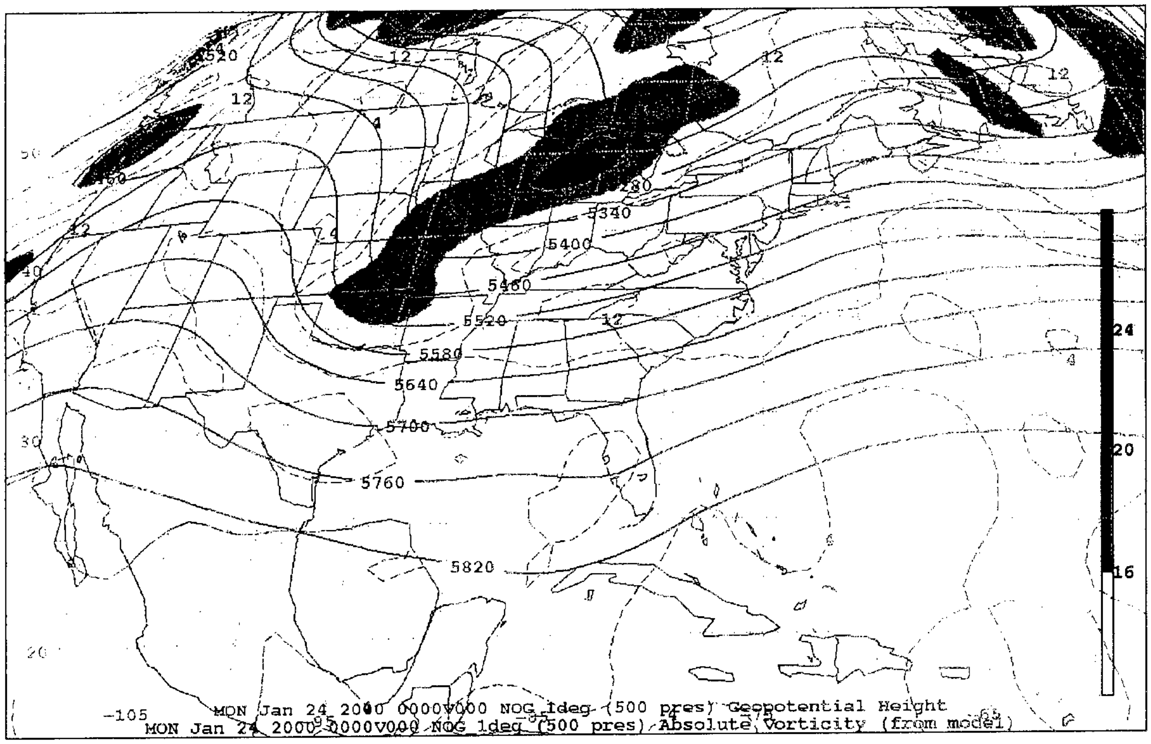


Figure 3.1. 24/00 500 mb Heights and Absolute Vorticity.

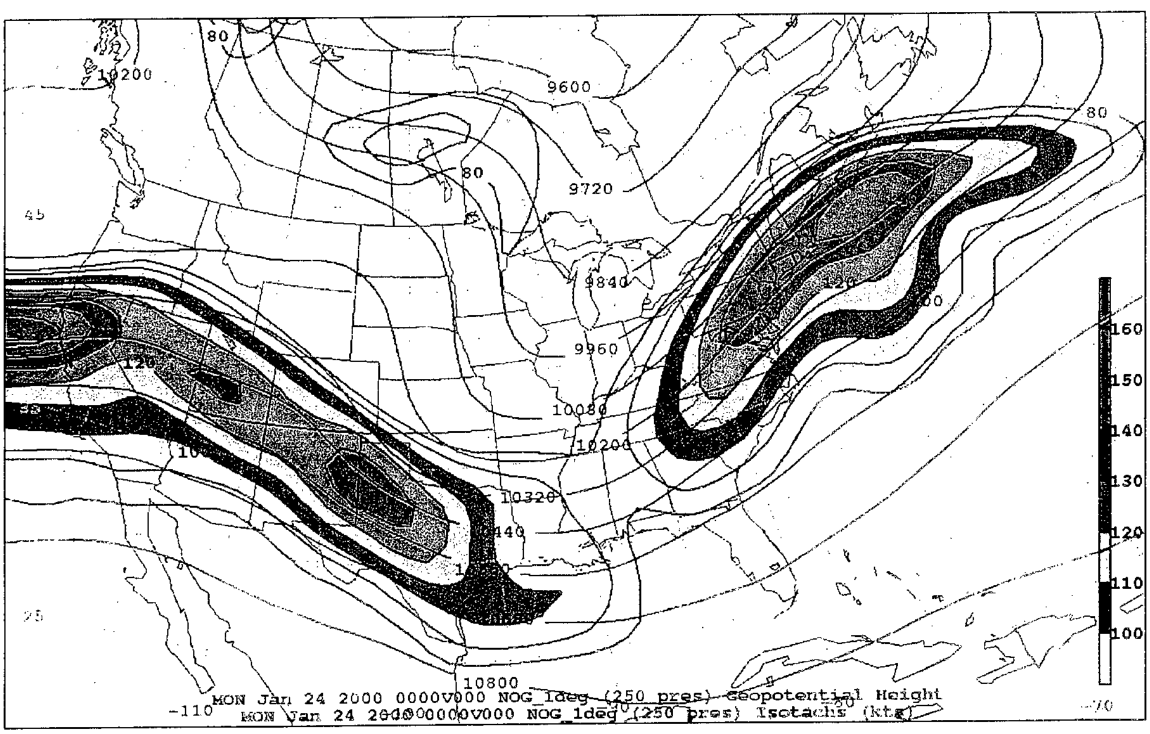


Figure 3.2. 24/00 250 mb Heights and Isotachs.

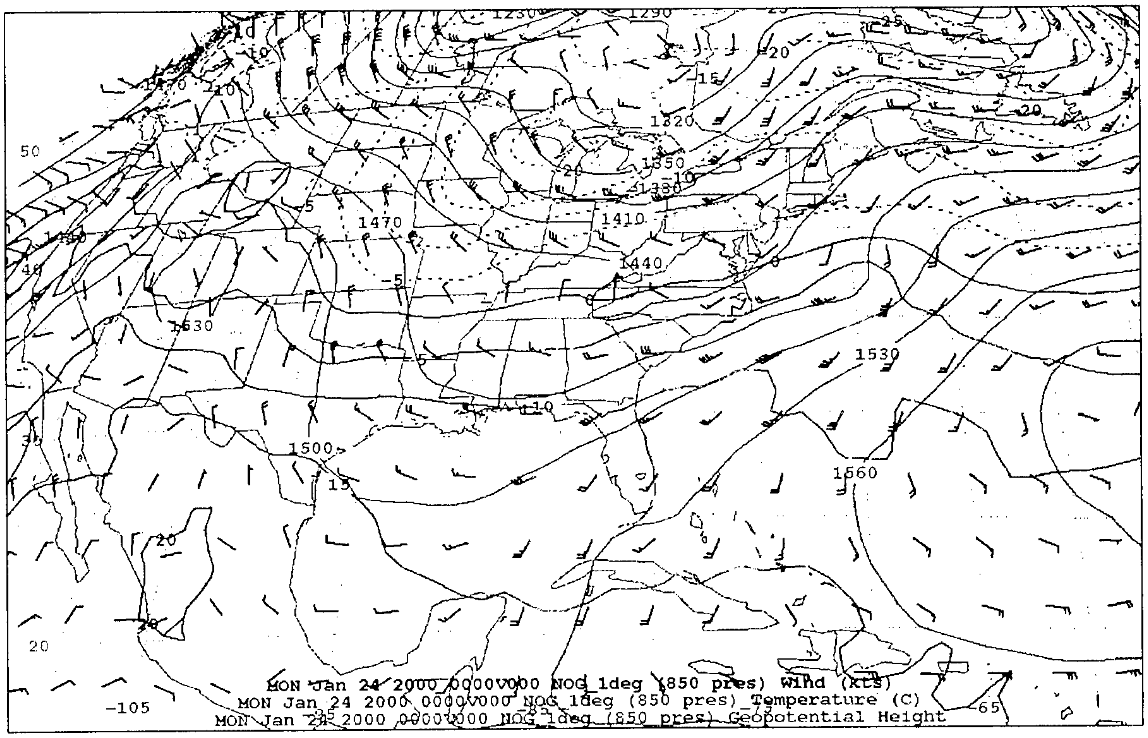


Figure 3.3. 24/00 850 mb Heights, Temperature and Wind.

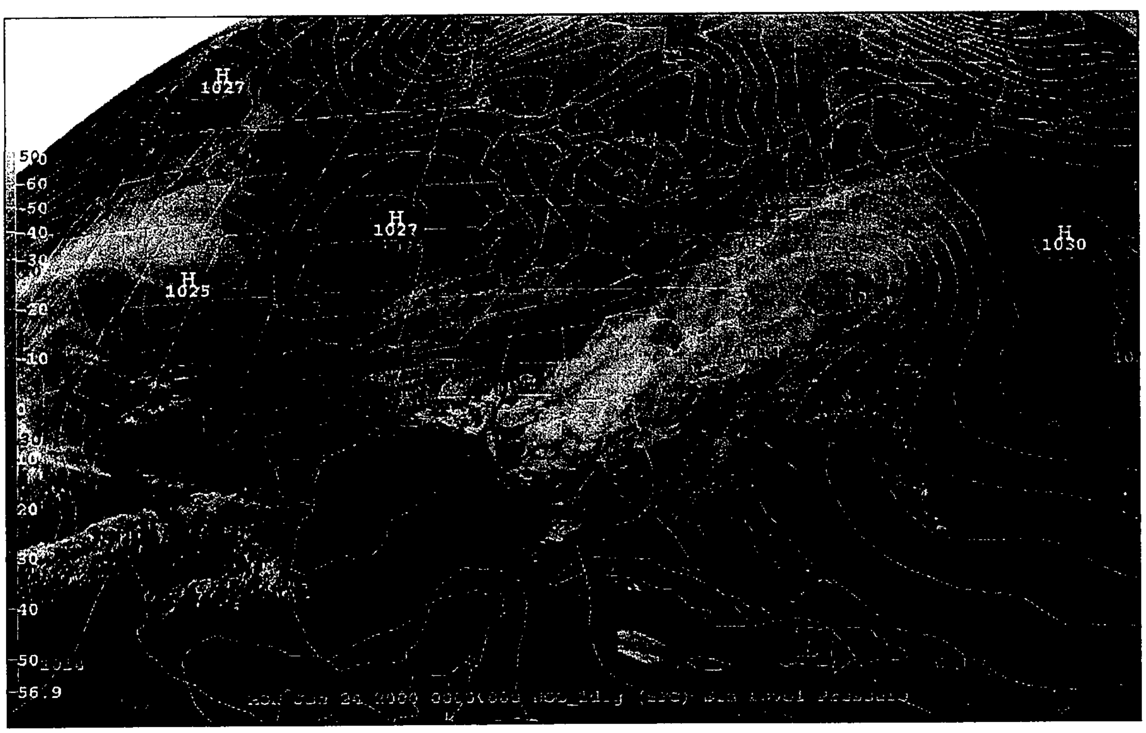


Figure 3.4. 24/00 Sea Level Pressure.

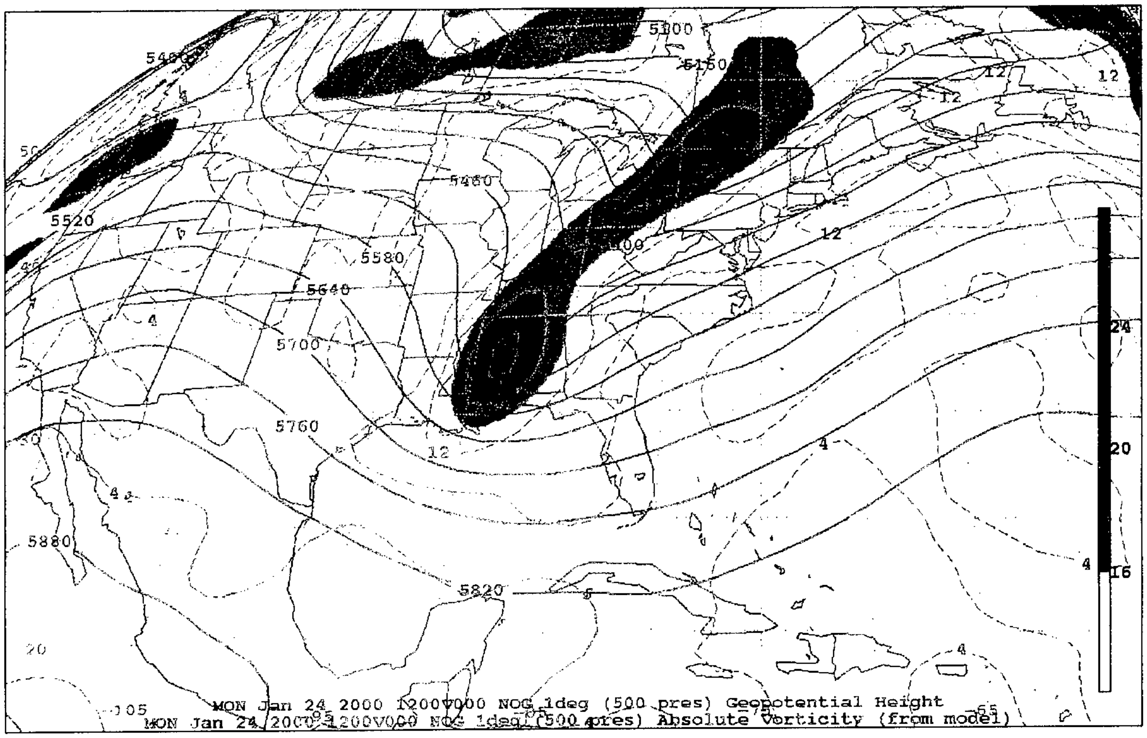


Figure 3.5. 24/12 500 mb Heights and Absolute Vorticity.

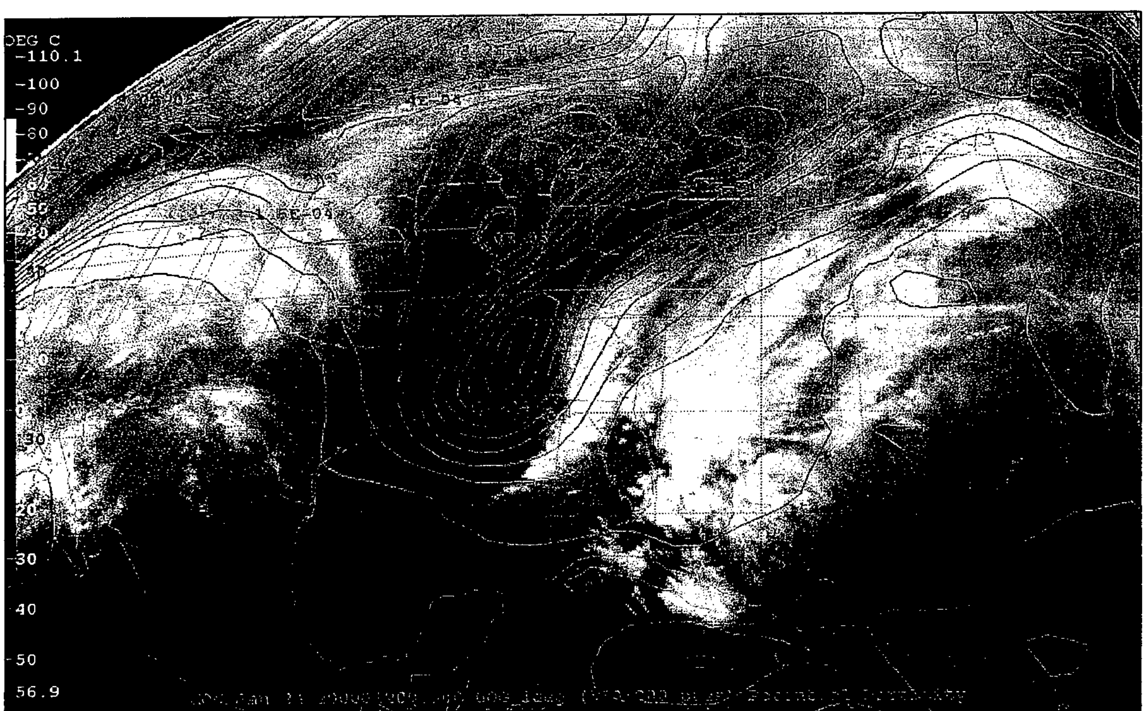


Figure 3.6. 24/12 500:200 mb Potential Vorticity.

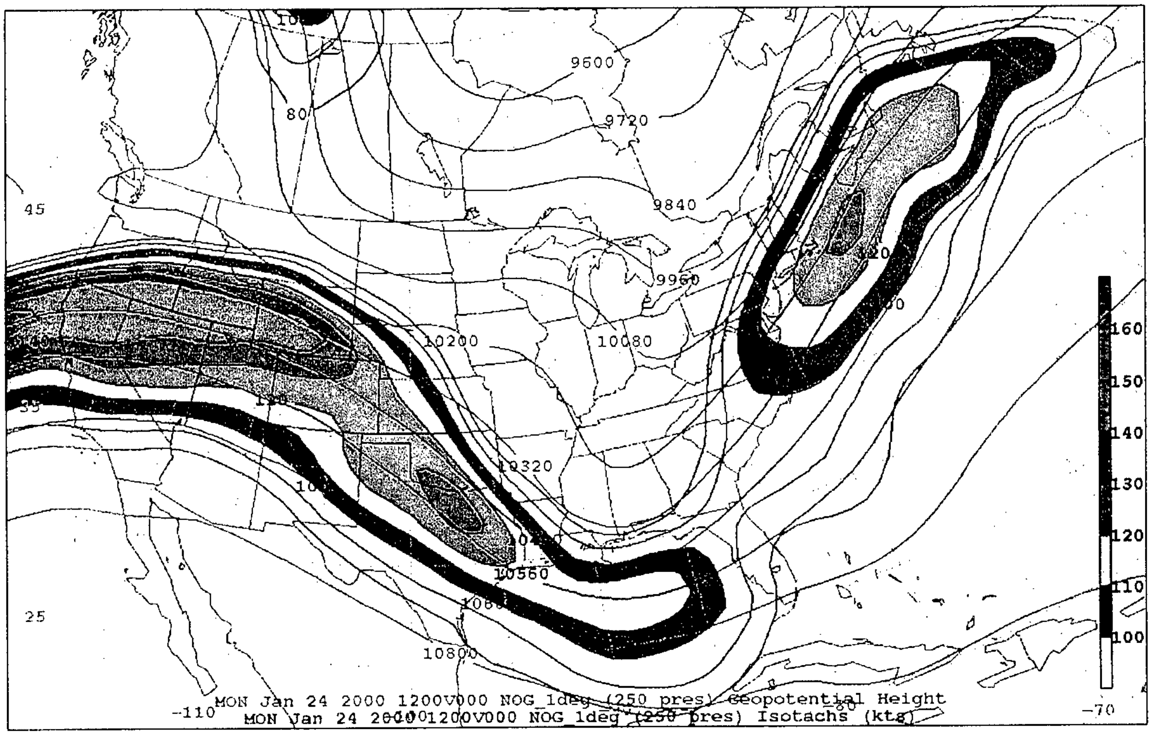


Figure 3.7. 24/12 250 mb Heights and Isotachs.

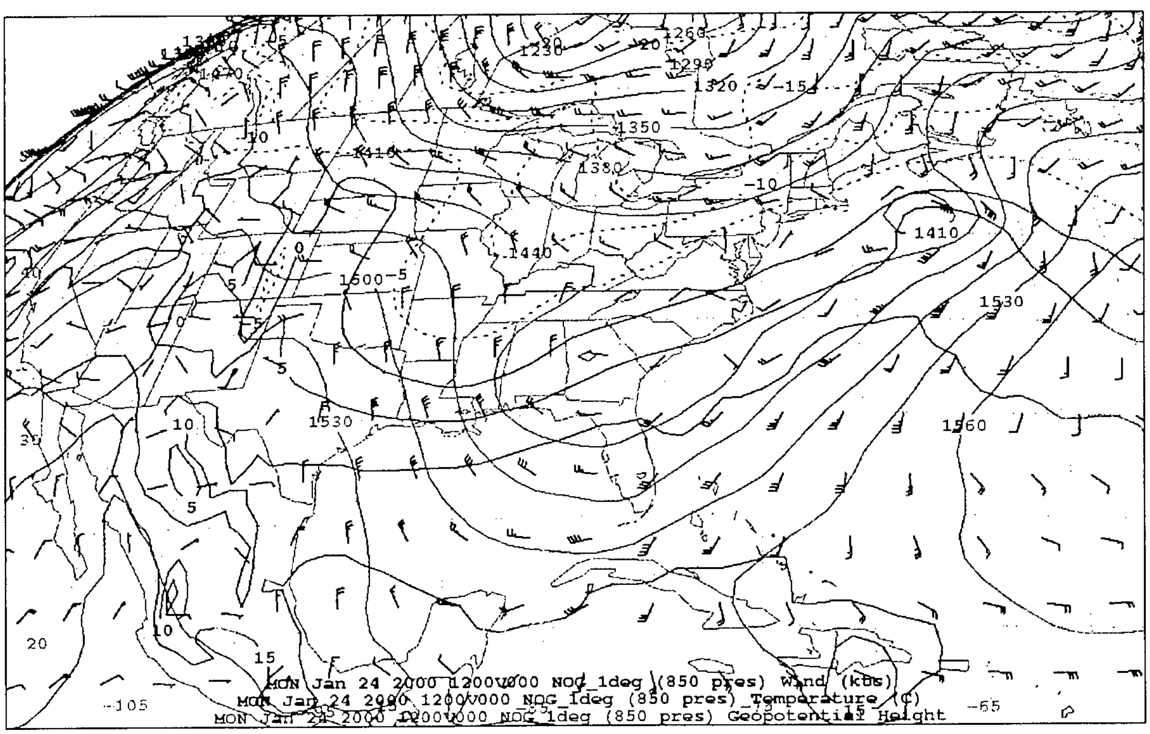


Figure 3.8. 24/12 850 mb Heights, Temperature and Wind.

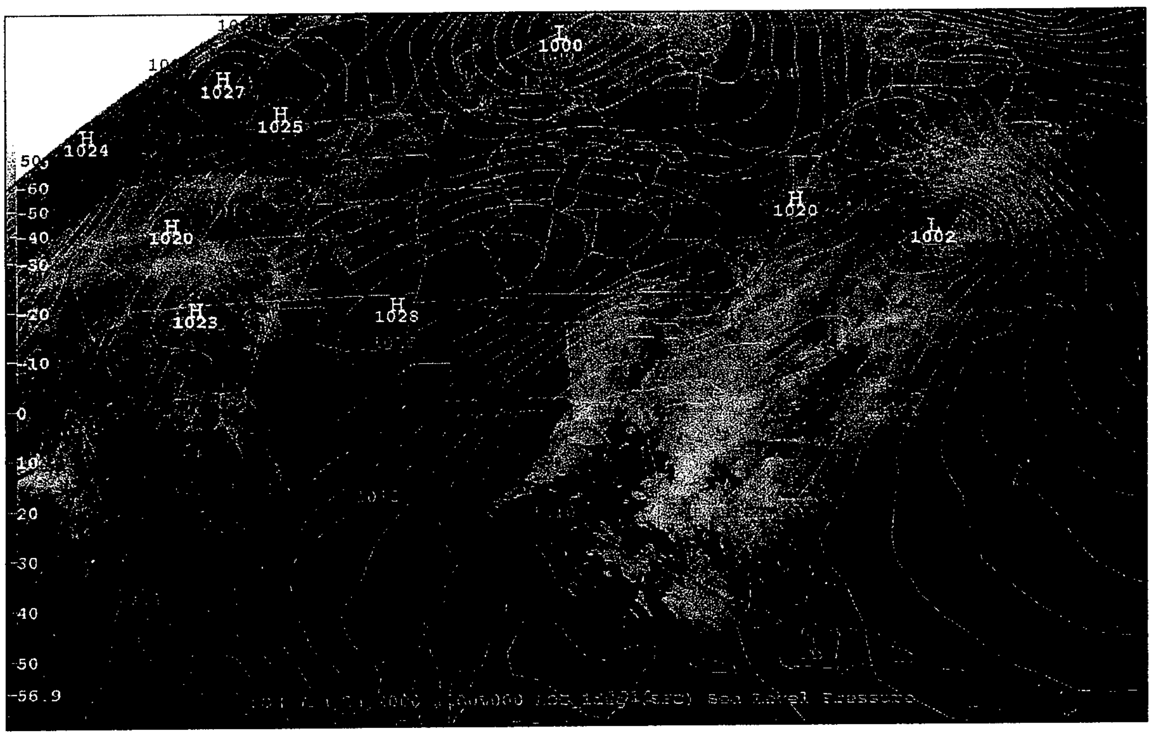


Figure 3.9. 24/12 Sea Level Pressure.

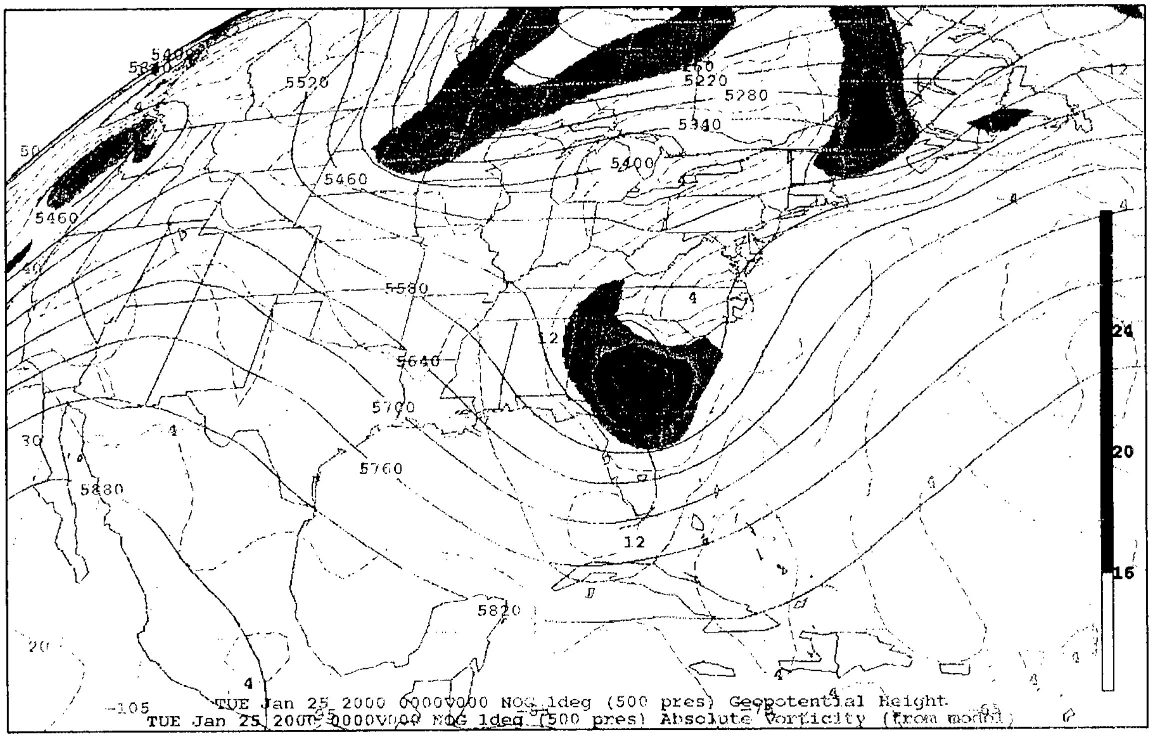


Figure 3.10. 25/00 500 mb Heights and Absolute Vorticity.

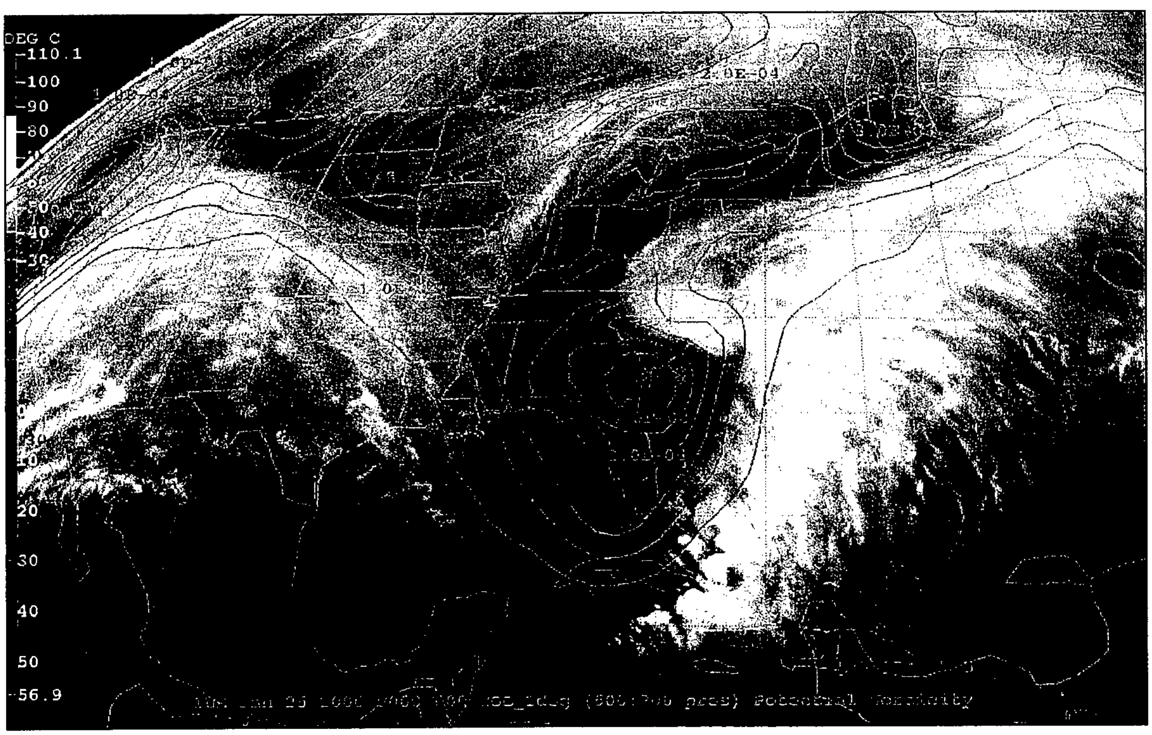


Figure 3.11. 25/00 500:200 mb Potential Vorticity.

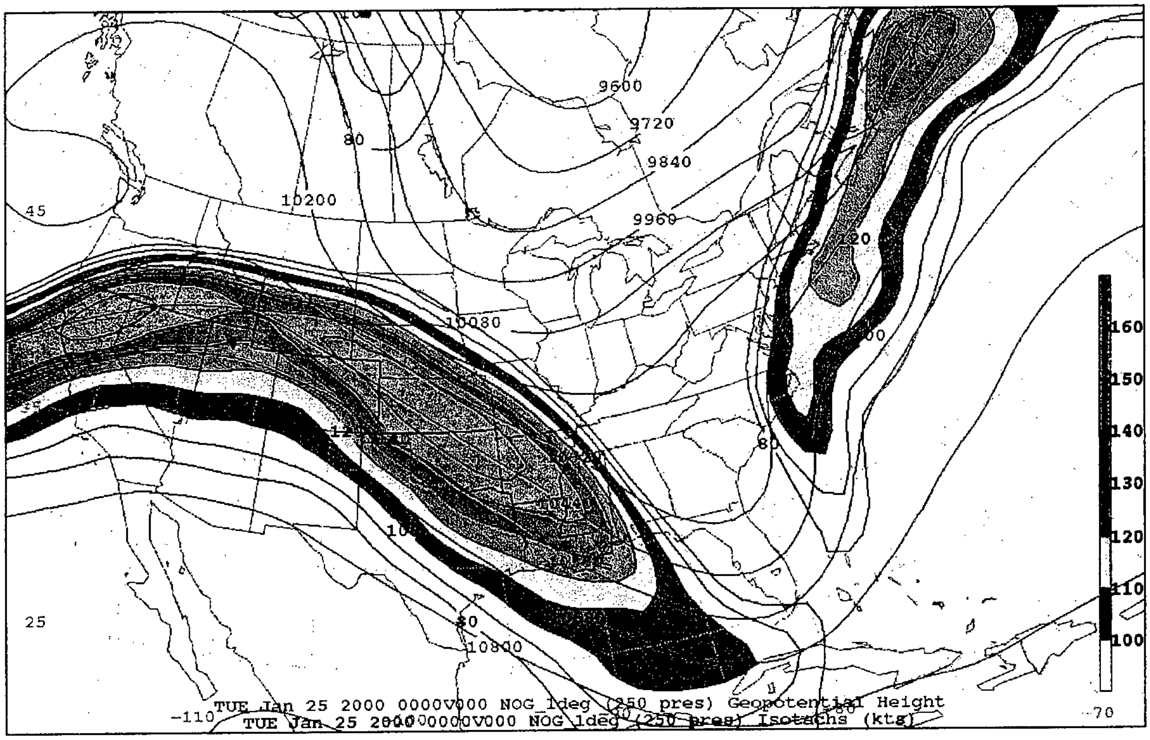


Figure 3.12. 25/00 250 mb Heights and Isotachs.

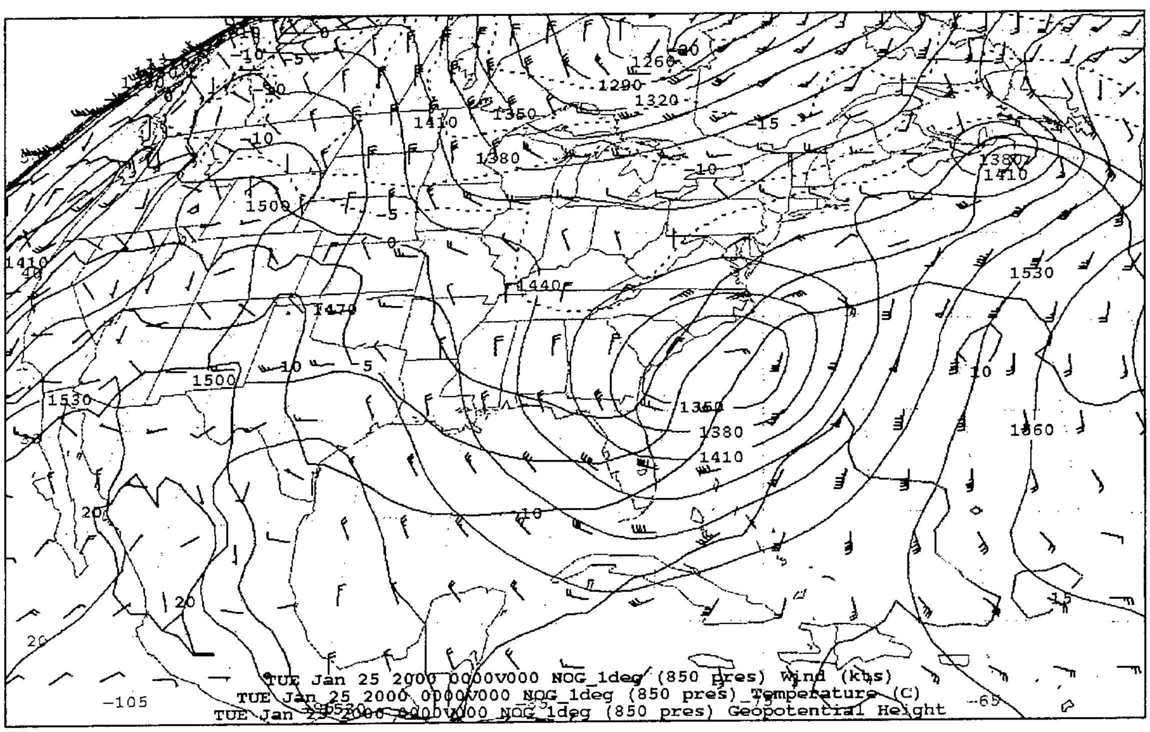


Figure 3.13. 25/00 850 mb Heights, Temperature and Wind.

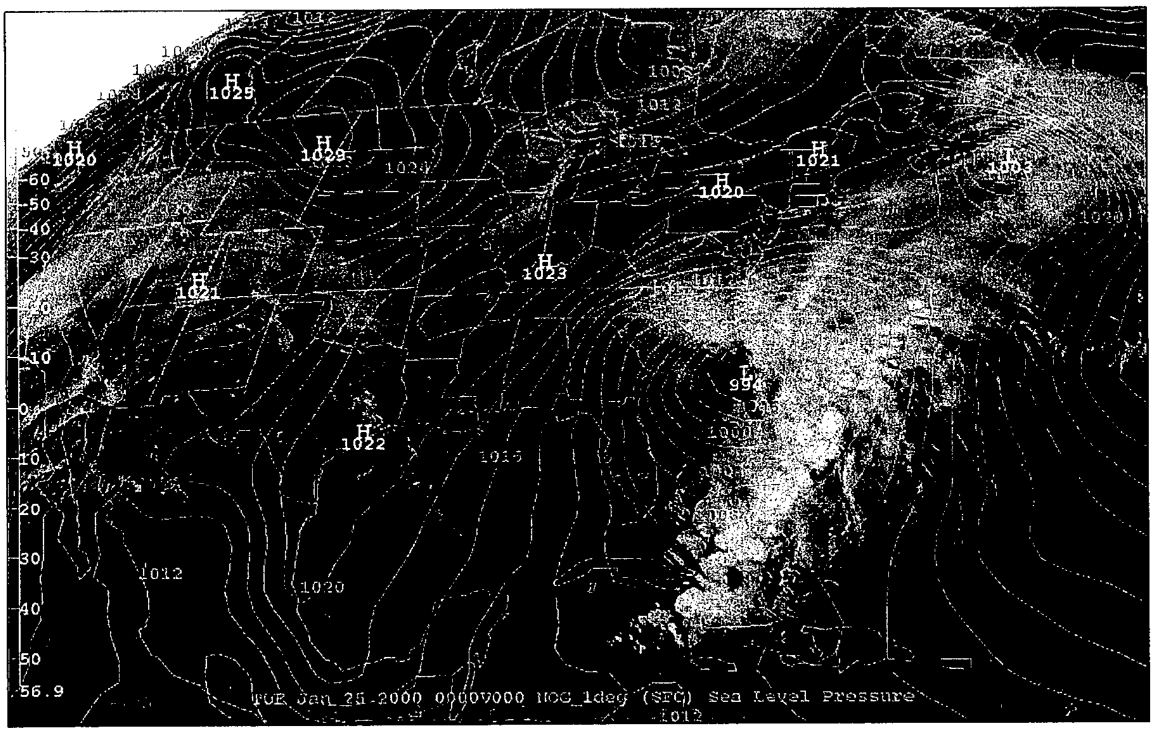


Figure 3.14. 25/00 Sea Level Pressure.

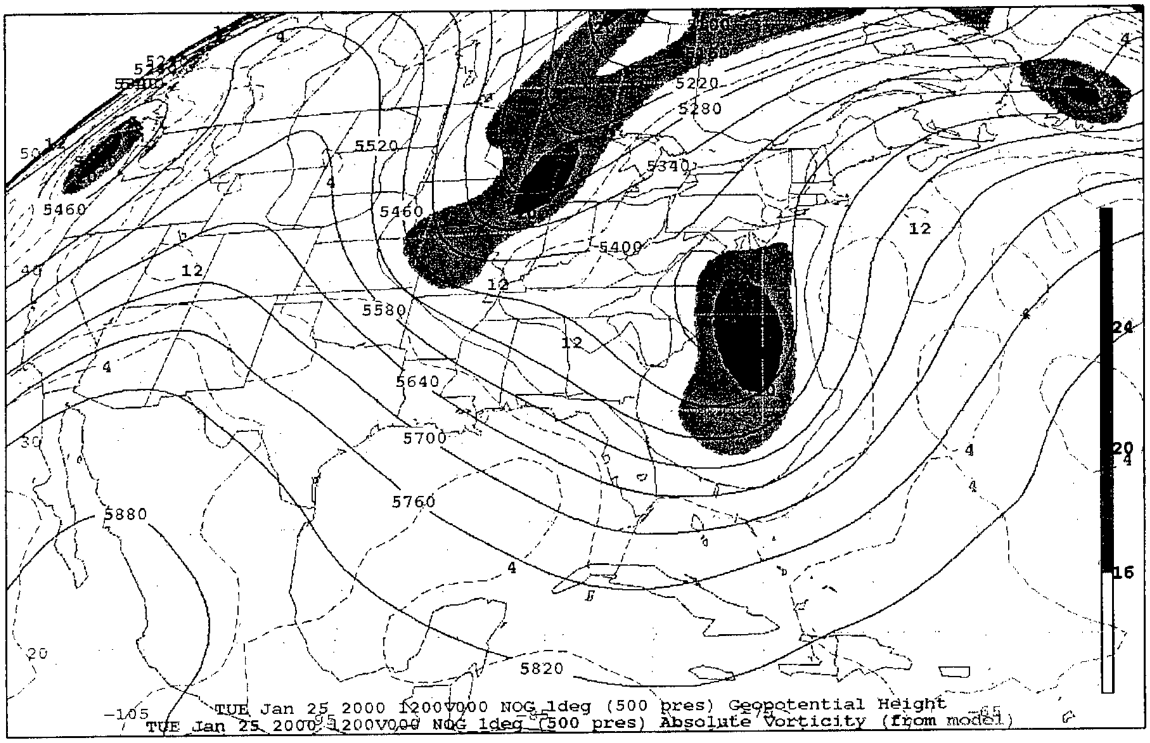


Figure 3.15. 25/12 500 mb Heights and Absolute Vorticity.

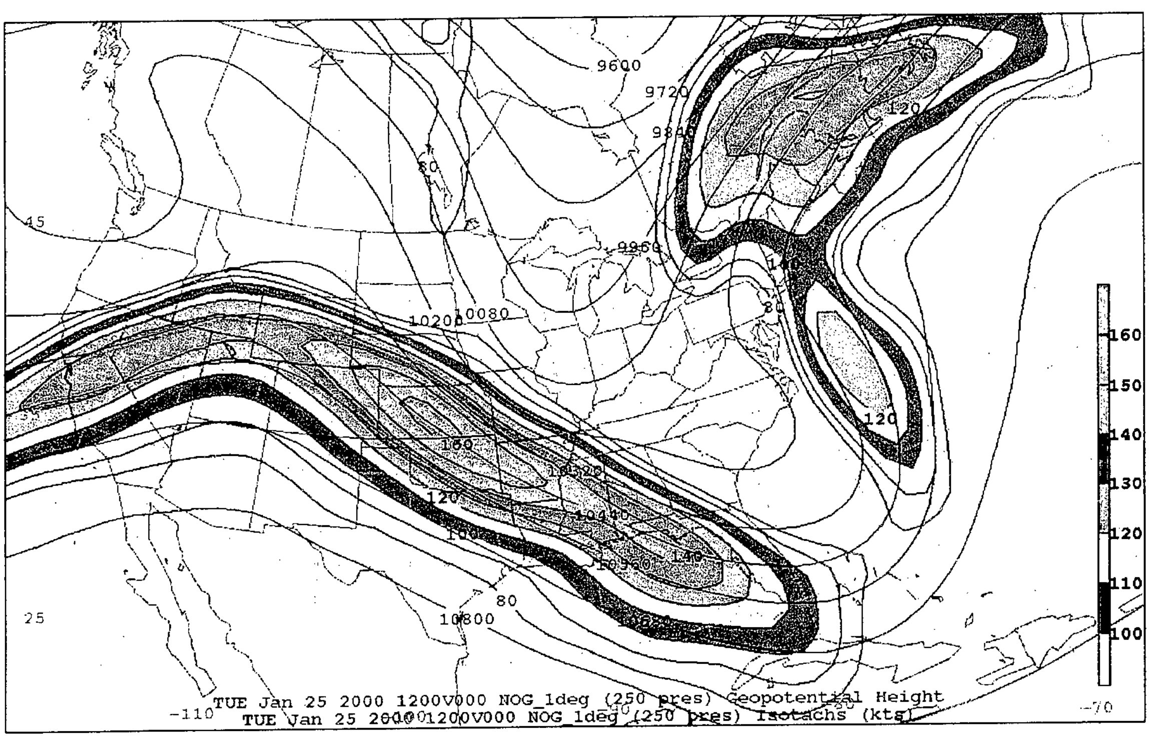


Figure 3.16. 25/12 250 mb Heights and Isotachs.

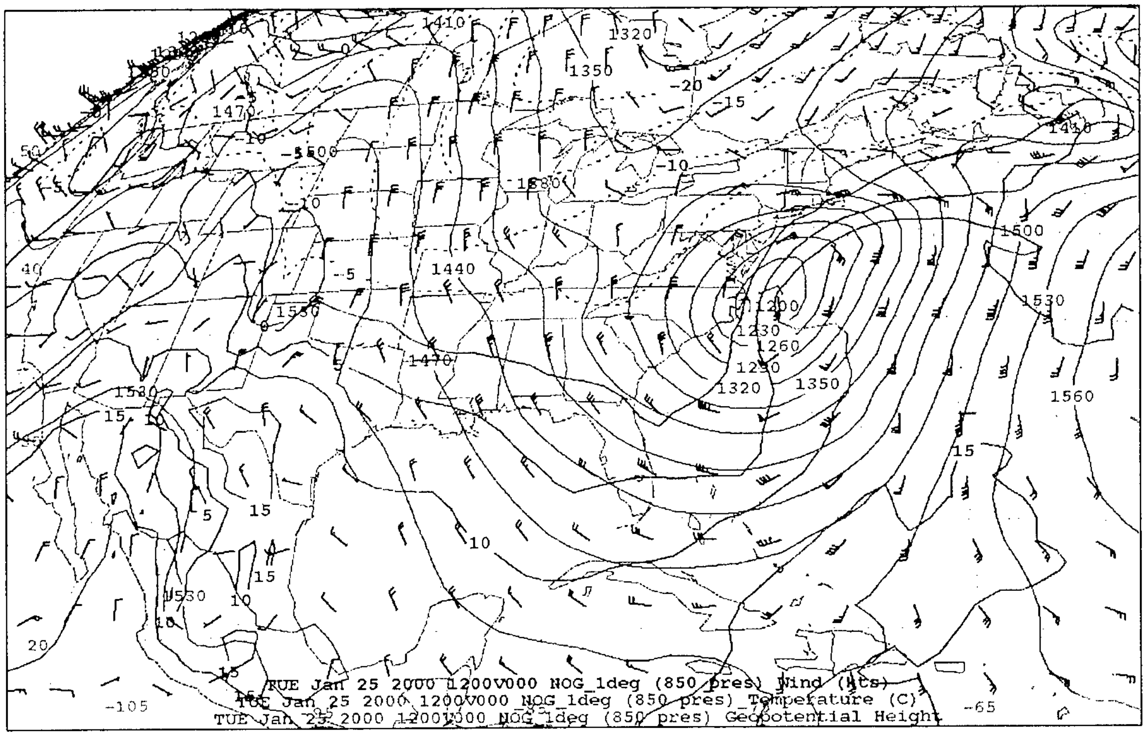


Figure 3.17. 25/12 850 mb Heights, Temperature and Wind.

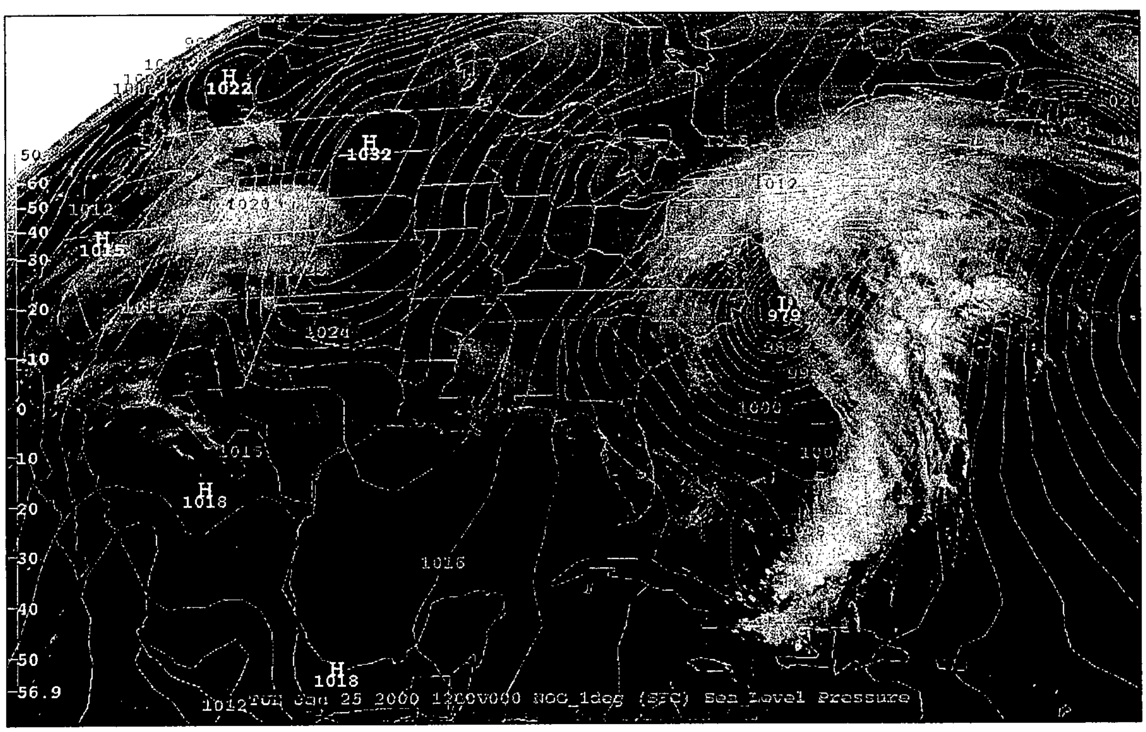


Figure 3.18. 25/12 Sea Level Pressure.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. OPERATIONAL MODEL PERFORMANCE

A. ACTUAL STORM TRACK

The actual evolution of the low is determined from the NWS manual analyses (Fig. A1 through A7) and buoy data. Hourly wind direction and MSLP time series of the buoy data are used to verify the accuracy of the NWS hand analysis. The manual analysis begins at 25/00 and the resultant storm track and sea-level pressure are shown in Fig. 4.1. During the period 25/00 to 26/00, the deepening system moved parallel to the East Coast, from just east of Cape Hatteras, NC to south of Long Island, NY.

Rapid deepening is underway at 25/00. During the six hour period of 25/00 to 25/06, the central pressure decreases 14 mb (994 mb to 980 mb). The pressure remains at 980 mb until 25/12, and then deepens further to its lowest central pressure of 976 mb by 25/18. The system begins filling after 25/18.

B. NOGAPS AND COAMPS ANALYZED TRACK AND INTENSITY

NOGAPS and COAMPS (West Atlantic) operational analyzed positions are shown in Fig. 4.2. It is evident that the NOGAPS analysis places the low too far to the southeast during the rapid deepening period. The 25/00 position is 125 km to the southeast and the 25/12 position is 75 km east of the hand analysis positions. Despite location errors, the deepening rates and central pressures are consistent with buoy data and manual analysis.

The analyzed position of the COAMPS track is very close to the NWS hand analysis and verifies well with buoy data. Figure 4.2 shows that COAMPS analyzed

cyclone positions are closer to the coast than NOGAPS. The COAMPS 25/00 analysis is 140 km to the west-northwest of NOGAPS, and the 25/12 position is 90 km to the west-northwest of NOGAPS. Note that the COAMPS analyses are within 15 km of the manual analysis at 25/00 and 25/12. While COAMPS produced better storm tracks, discrepancies exist in the central pressures and deepening rates.

The NOGAPS analysis (Fig. 4.3) shows rapid deepening from 24/12 to 25/12, with a decrease of 28 mb in the 24 h period (1007 mb to 979 mb). From 24/12 to 25/00, the pressure fall is 13 mb, and from 25/00 to 25/12 there is another 15 mb drop. Figure 4.3 shows NOGAPS lowest central pressure is 978 mb at 26/00. Manual analysis and buoy analysis document the lowest pressure as 976 mb at 25/18.

Figure 4.3 shows COAMPS only analyzed one 12 h period of rapid deepening. In this period, between 24/12 to 25/00, the central pressure drops from 1007 mb to 991 mb for a 16 mb decrease in 12 h. The 991 mb value at 25/00 is lower than the hand analysis, NOGAPS, and buoy data, which all indicate 994 mb. The lowest COAMPS central pressure of 983 mb occurs at 26/00. The timing of the lowest pressure is consistent with hand analysis, but the minimum pressure is not low enough, because the excessive deepening rate from 24/12 to 25/00 is followed by a weaker deepening rate from 25/00 to 25/12.

C. NOGAPS FORECAST TRACK AND INTENSITY ERRORS

Comparisons of forecast position and intensity are made with the appropriate verifying analysis from the same model. It must be noted that some cyclone position analysis errors were present at 25/00 and 25/12 as previously mentioned. Figure 4.4 illustrates the ability of NOGAPS to predict the deepening of this cyclone. All the

NOGAPS runs from 24/00 to 25/12 captured the rapid deepening period, however there is some variation in the final central pressure. The poorest forecast (24/00) does not drop the central pressure enough and starts to fill the cyclone at 25/12, 12 h too early.

When considering the NOGAPS forecast cyclone position, forecast runs had a tendency to place the storm too far east and move it too fast. These errors are important for the valid times of 25/00, 25/12, and 26/00. Figure 4.5 shows significant positional errors in the 24/00 run beginning with the 24 h forecast (valid at 25/00). Propagation speed is a problem as the storm moves too fast and too far to the east. The 24 h forecast (valid at 25/00) is 215 km to the east-northeast of the analyzed position. The 36 h forecast (valid at 25/12) is 490 km to the northeast and the 48 h forecast (valid at 26/00) shows an 860 km placement error. These are large position errors for short range forecasts.

The track placement is better with the 24/12 run, but significant errors are still present (Fig. 4.6). Again, the low propagates too fast and too far east. The 12 h forecast (valid at 25/00) is 130 km to the southeast of the analyzed position. By 24 h (valid at 25/12) it is 400 km to the northeast. This signifies an exceptionally large speed error as the forecast low moves from southeast to northeast of the analysis track. The 36 h forecast (valid at 26/00) is 360 km to the east-northeast of the verifying analysis.

The 25/00 run is initialized after cyclogenesis had begun. The 12 h forecast deepens the system 12 mb (994 mb to 982 mb), then over-deepens the system in the 24 h forecast to the lowest central pressure of 975 mb at 26/00. Figure 4.7 shows a satisfactory 12 h forecast placement (valid at 25/12). However, positional errors grow by the 24 h forecast (valid at 26/00) with the low positioned 185 km too far east.

D. NOGAPS FORECAST PRECIPITATION ERRORS

NOGAPS precipitation forecast graphics show the predicted accumulated precipitation over the previous 12 h. These forecasts are not a snap shot and care must be taken when comparing them to real time or near real time products such as satellite imagery and radar that do show an instantaneous description of the current weather. When verifying model precipitation performance, it is necessary to look at the progression of radar and satellite data from the entire 12 h period for which the model is forecasting. As discussed in Chapter III, heavy snow began falling just after 25/00 and continued over the next 12 to 18 hours. It is apparent that a good precipitation forecast valid at 25/12 is crucial for this storm. This section will discuss NOGAPS precipitation forecasts for valid time 25/12 from the 24/00, 24/12, and 25/00 runs. The 25/12 IR image is presented in Fig. 4.8, and verifying radar imagery is contained in the Appendix (Fig. A21).

The 36 h forecast from the 24/00 run (valid at 25/12) in Fig. 4.9 shows that the heavy precipitation associated with the bent back cloud pattern is not depicted. It is this feature that correlates with the heavy snow band shown in the NWS hand analyzed snowfall amounts (Fig. A8). The failure to predict this feature can be traced back to the 12 h forecast from this run (not shown), where the approaching baroclinic leaf (see Fig. 3.9) was not forecast. The 36 h forecast also places a heavy precipitation band in the Atlantic that does not match IR imagery. The forecast precipitation is too far to the south and east, correlating with errors in the placement of the low.

Figure 4.10 shows that the 24 h forecast from the 24/12 run (valid at 25/12) also fails to depict the bent back feature. Minimal precipitation is forecast for the location of

the heavy snow band. The forecast places the heaviest precipitation offshore and does not correlate with IR imagery or radar data.

The 12 h forecast from the 25/00 run (valid at 25/12) attempts to forecast the bent back feature, but positions it improperly (Fig. 4.11). Heavy snow has been falling from Maryland through central Virginia and central North Carolina. The NOGAPS forecast shows the heavy precipitation too far to the south and east of the true position. However, distinct precipitation maximums are developed along the warm front and cold front, which verify well with the IR imagery.

E. COAMPS FORECAST TRACK AND INTENSITY ERRORS

As mentioned in Section B of this chapter, the cyclone positions in the COAMPS analyses are very good. As a result of the better analysis positions and higher model horizontal and vertical resolution, the forecast positions from COAMPS are generally better than from NOGAPS. However, early COAMPS runs still show some positional errors, mainly due to propagation speed.

Figure 4.12 illustrates the ability of COAMPS to predict the deepening of the cyclone. All the COAMPS runs capture a rapid deepening period, however there is some variation in the length of the rapid deepening period and the final central pressure. Both the 24/00 and 24/12 runs correctly capture a 24 h rapid deepening period between 24/12 and 25/12, with the 24/00 run displaying the largest pressure drop (30 mb) for the 24 h period.

The storm track of the 24/00 run is too far east and the forecast cyclone propagates too fast (Fig. 4.13). The 24 h forecast (valid at 25/00) is 125 km to the southeast of the analyzed position, while the 36 h forecast (valid at 25/12) places the low

210 km to the northeast. This signifies a large speed error, moving the low from a southeast error position to a northeast error position. The forecast low also deepens 17 mb from 25/00 to 25/12 while the model analysis only drops 6 mb in this 12 h period. However, the NWS manual analysis shows a 14 mb decrease in the same 12 h period, suggesting the forecast central pressures are better than the analysis central pressures. Propagation speed errors continue into the 48 h forecast (valid at 26/00), which shows a 420 km error to the northeast. In general, the track direction is successful after 25/00, but it is just too far east and fast.

The 24/12 run produces a satisfactory position forecast through the first 36 h. Figure 4.14 shows a COAMPS tendency to place the storm too far east and propagate it too fast. The 12 h forecast (valid at 25/00) was only 25 km east of the verifying analysis, and the 24 h forecast (valid at 25/12) was only 60 km to the east-northeast of its verifying analysis. The central pressure deepens 11 mb from 25/00 to 25/12, compared to only a 6 mb decrease in the verifying analyses. Some speed errors were evident by the 36 h forecast (valid at 26/00), with the low positioned 185 km too far to the north-northeast.

The storm track of the 25/00 run is very good, considering this run was initialized about one-half way through the rapid deepening period. Figure 4.15 shows that the 12 h forecast (valid at 25/12) is only 20 km to the north of the verifying analysis. Some speed errors affect later forecasts, placing the 24 h forecast (valid at 26/00) 105 km to the north of the verifying analysis.

F. COAMPS FORECAST PRECIPITATION ERRORS

Following the NOGAPS discussion in Section D, this section will review COAMPS precipitation forecasts for valid time 25/12 from the 24/00, 24/12, and 25/00

runs. Recall that the 25/12 IR image is presented in Fig. 4.8, and verifying radar imagery is contained in the Appendix (Fig. A21).

The 36 h forecast from the 24/00 run (valid at 25/12) does not depict the bent back feature (Figure 4.16), but some overland precipitation is shown along the North Carolina coast. The forecast heavy precipitation is displaced to the east of IR and radar imagery. Like with NOGAPS, the errors with this forecast can be traced back to the 12 h forecast from this run where the precipitation associated with the baroclinic leaf was not captured.

The 24 h forecast from the 24/12 run (valid at 25/12) attempts to resolve the bent back feature (Figure 4.17). The forecast places it to the east along the North Carolina coast, where as radar and IR imagery place it in the central Carolinas. The heavy precipitation in the western Atlantic matches IR imagery well. The 12 h forecast (not shown) managed to capture the baroclinic leaf structure and was able to develop it in the later forecasts.

The 12 h forecast from the 25/00 run (valid at 25/12) is a good forecast. The heavy precipitation band is forecast, however, the position remains too far east (Figure 4.18). Placement errors cause the coastal Carolinas to be impacted, rather than the central part of North Carolina and Virginia. The cold frontal precipitation in the western Atlantic matches IR imagery well, while the precipitation associated with the warm front is slightly south of the IR imagery.

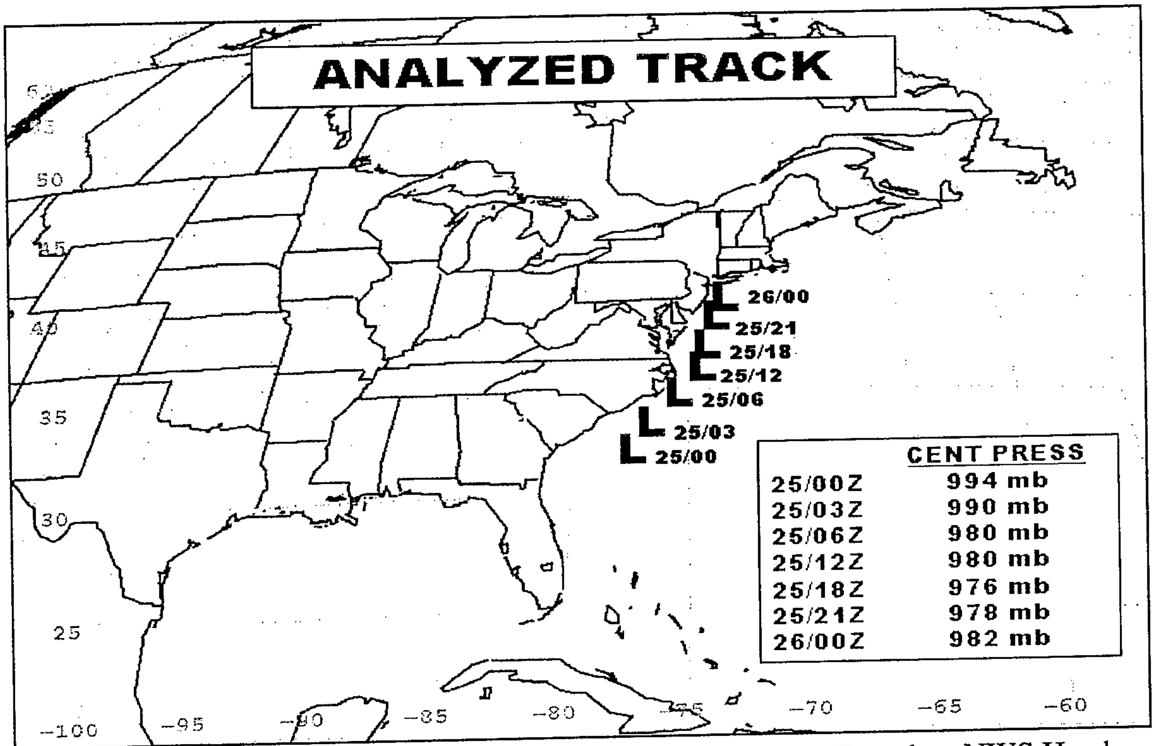


Figure 4.1. Cyclone Center Locations and Central Pressures. Based on NWS Hand Analysis and Buoy Data from the National Buoy Data Center and Other Observations.

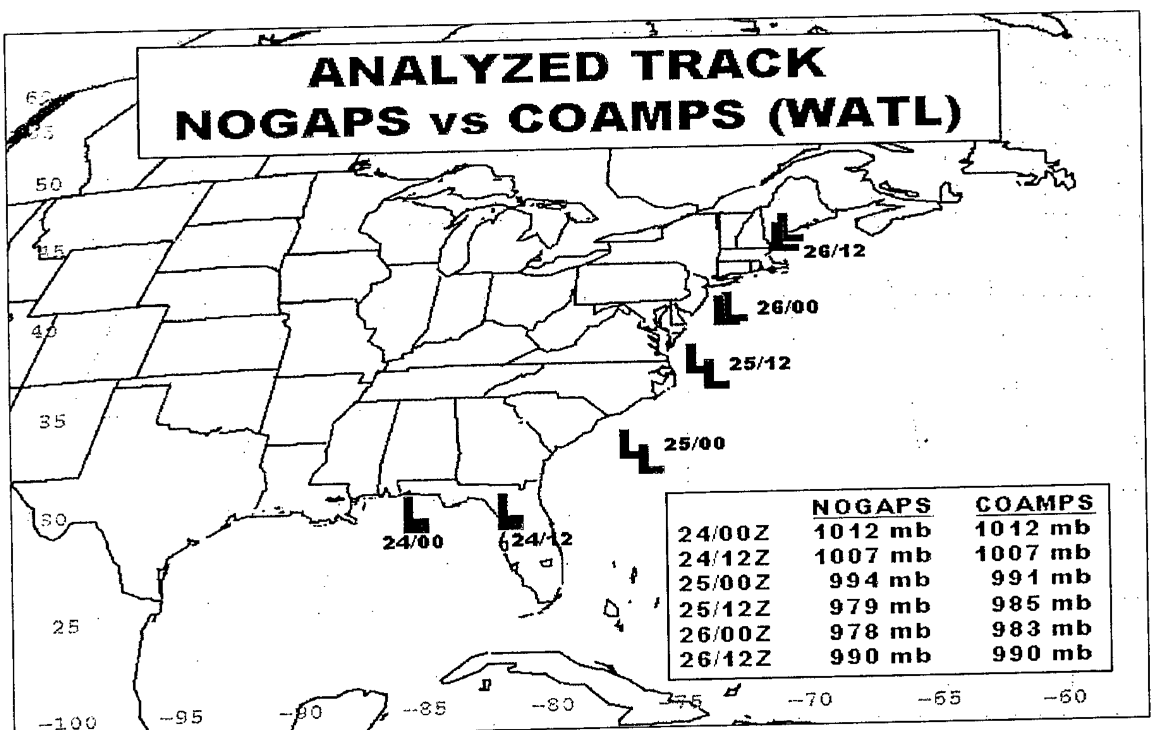


Figure 4.2. NOGAPS and COAMPS (West Atlantic) Analyzed Track and Intensity.

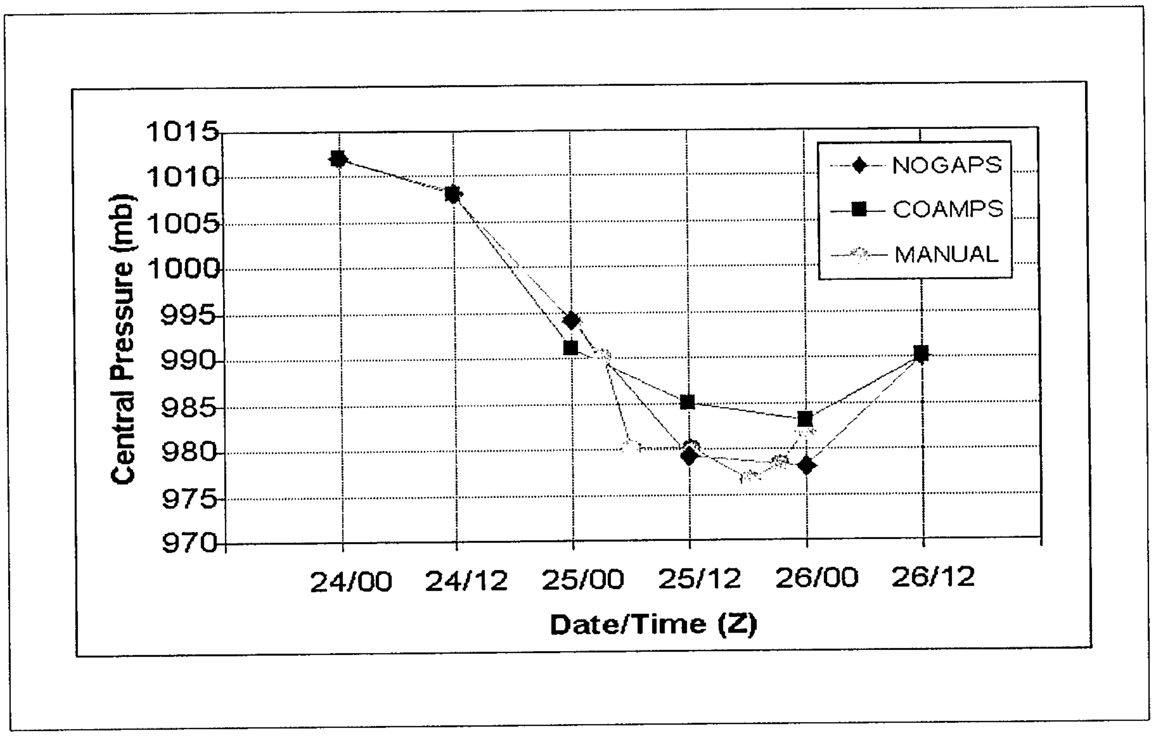


Figure 4.3. NOGAPS and COAMPS Analyzed Central Pressure with Manual Analysis Values.

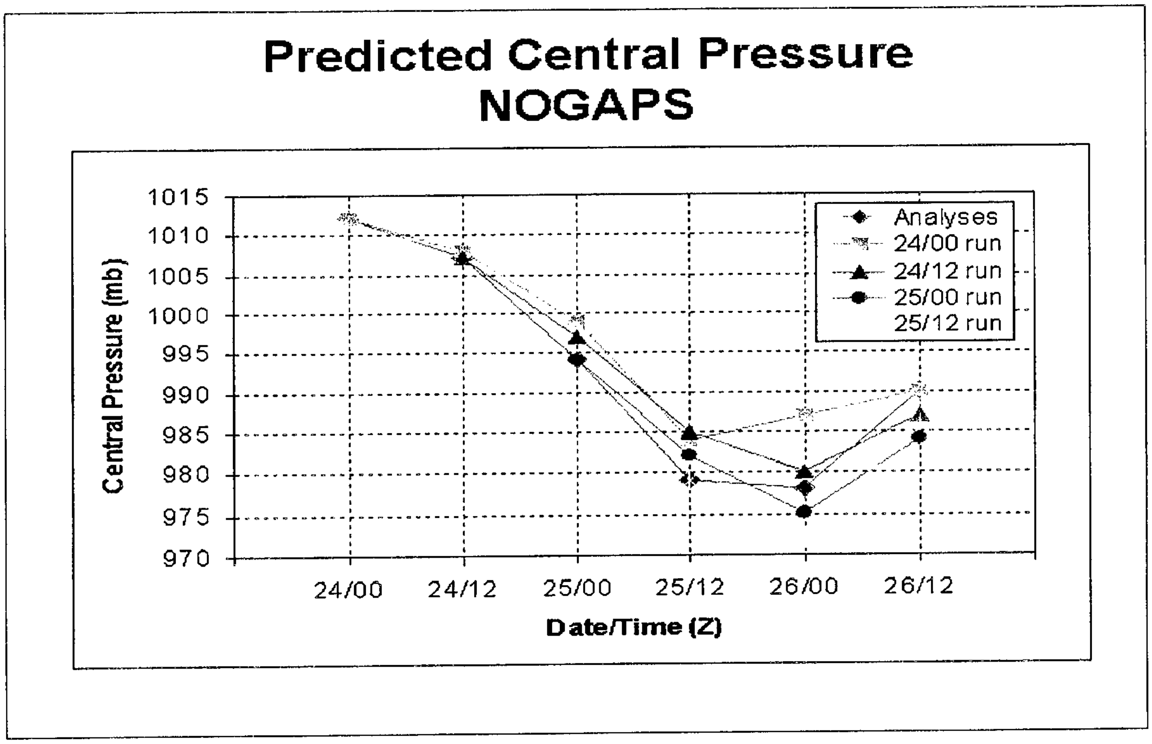
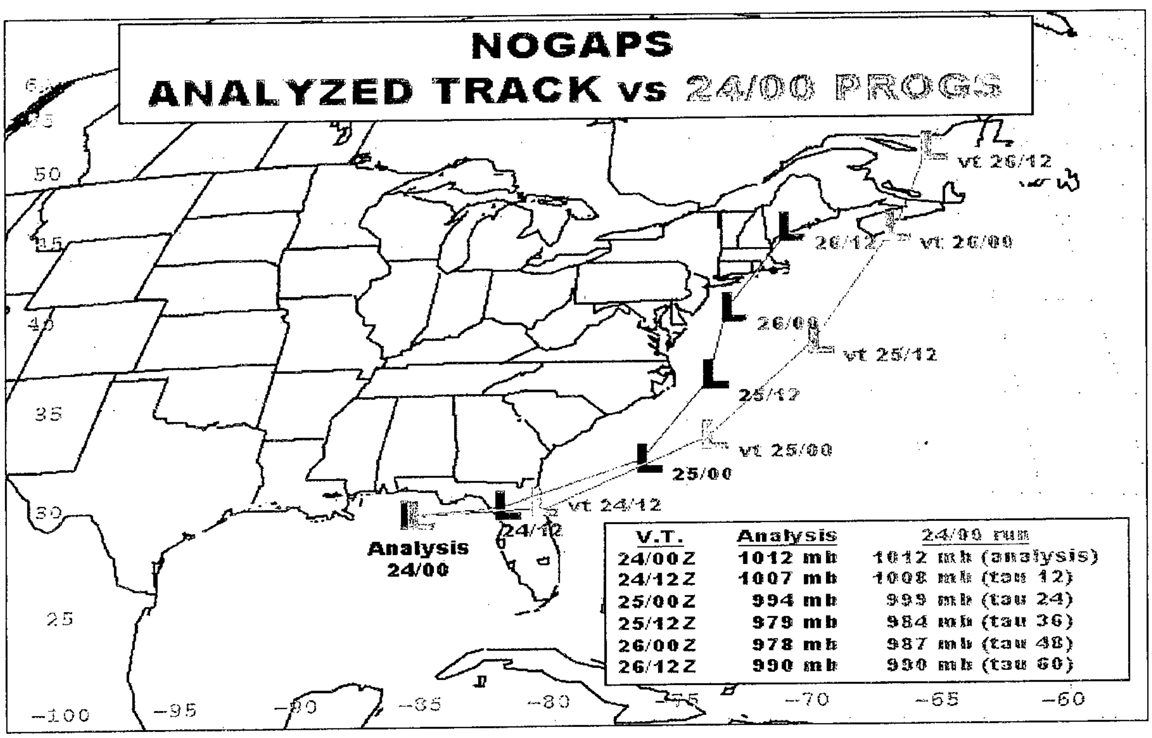


Figure 4.4. NOGAPS Forecast Central Pressure.



V.T.	Analysis	24/00 run
24/00Z	1012 mb	1012 mb (analysis)
24/12Z	1007 mb	1008 mb (tau 12)
25/00Z	994 mb	999 mb (tau 24)
25/12Z	979 mb	984 mb (tau 36)
26/00Z	978 mb	987 mb (tau 48)
26/12Z	990 mb	990 mb (tau 60)

Figure 4.5. NOGAPS Analyzed Track and 24/00 Run.

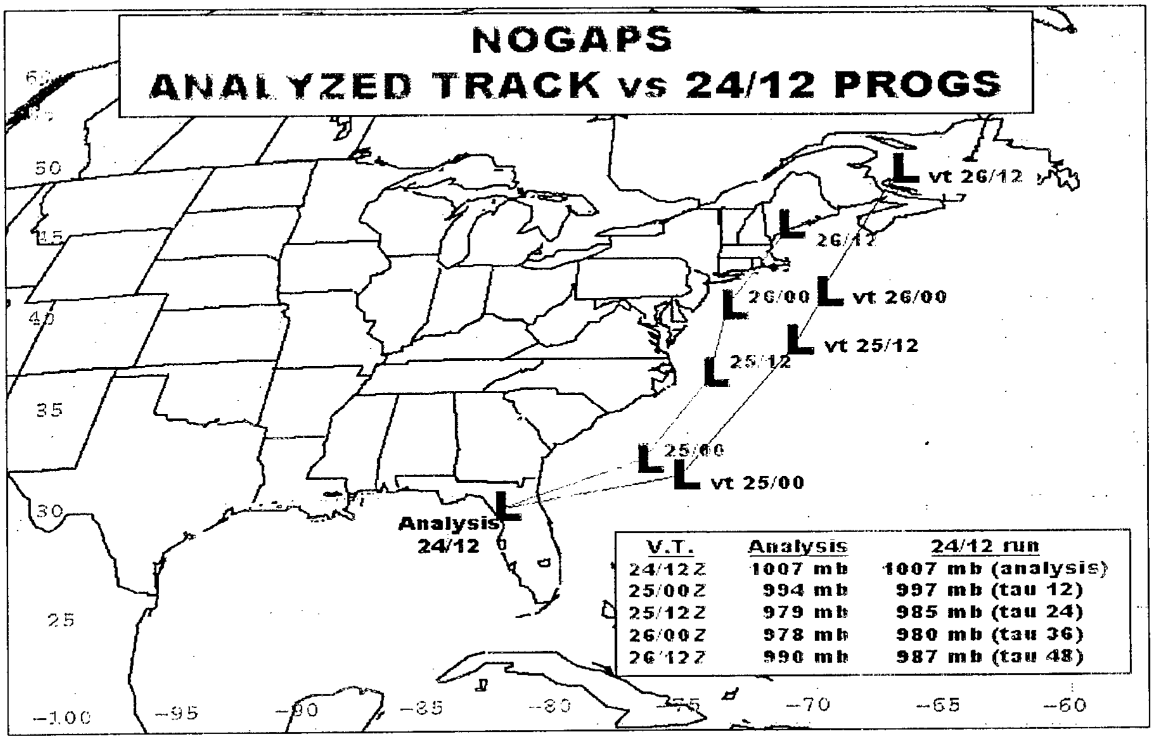


Figure 4.6. NOGAPS Analyzed Track and 24/12 Run.

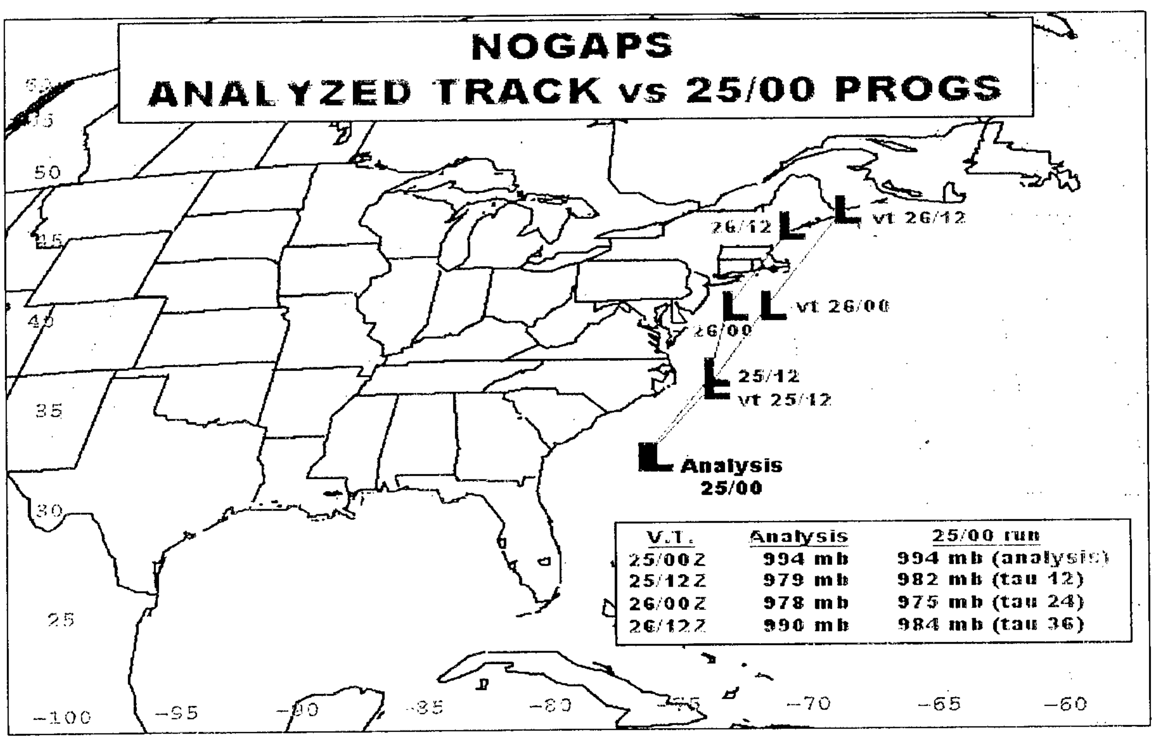


Figure 4.7. NOGAPS Analyzed Track and 25/00 Run.

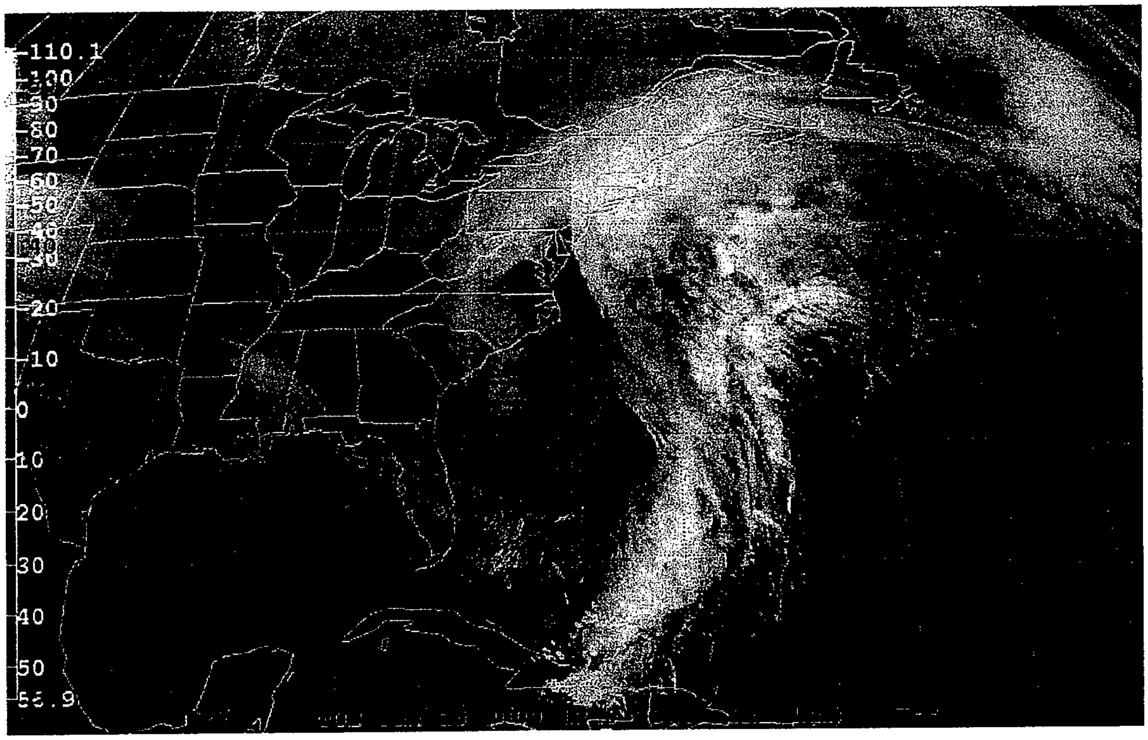


Figure 4.8. IR imagery for 25/12

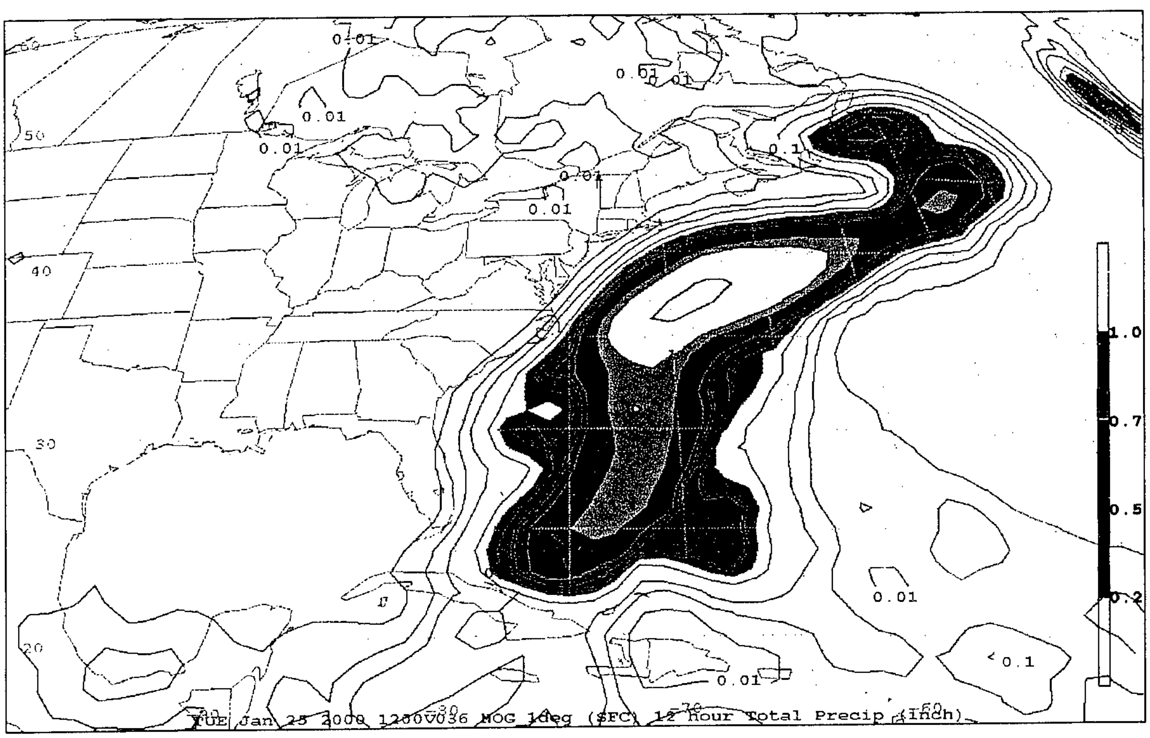


Figure 4.9. NOGAPS 36-Hour Precipitation Forecast from the 24/00 Run, Valid at 25/12.

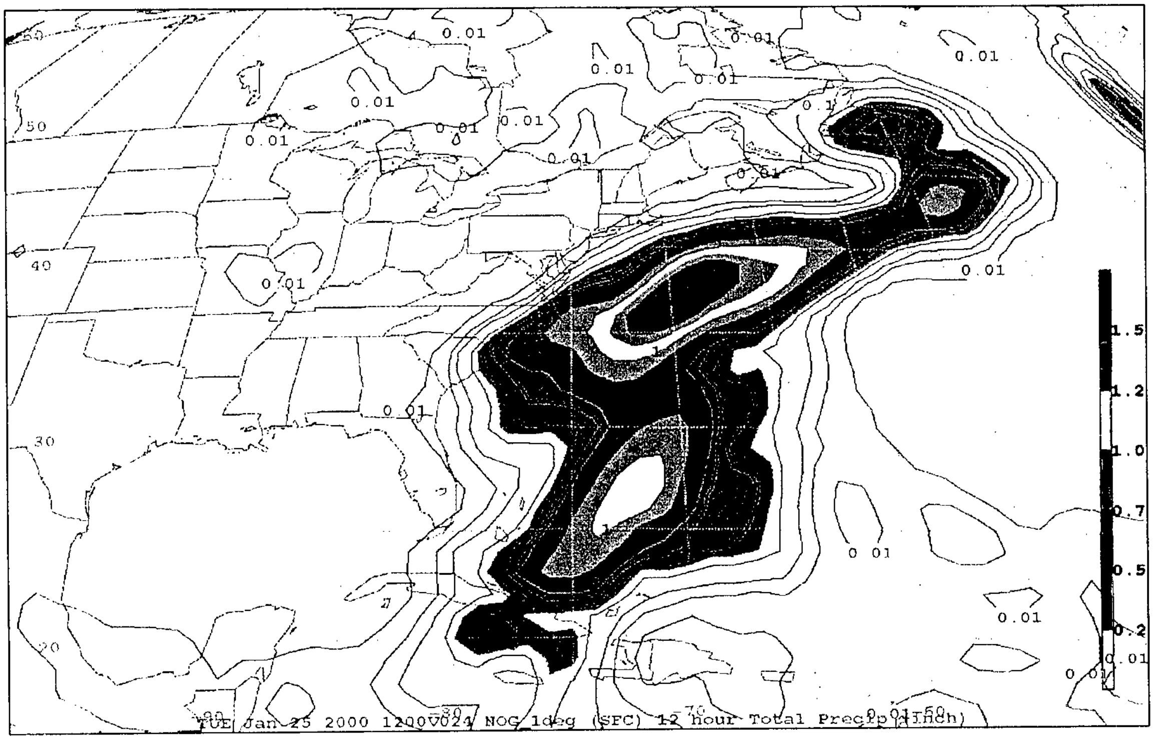


Figure 4.10. NOGAPS 24-Hour Precipitation Forecast from the 24/12 Run, Valid at 25/12.

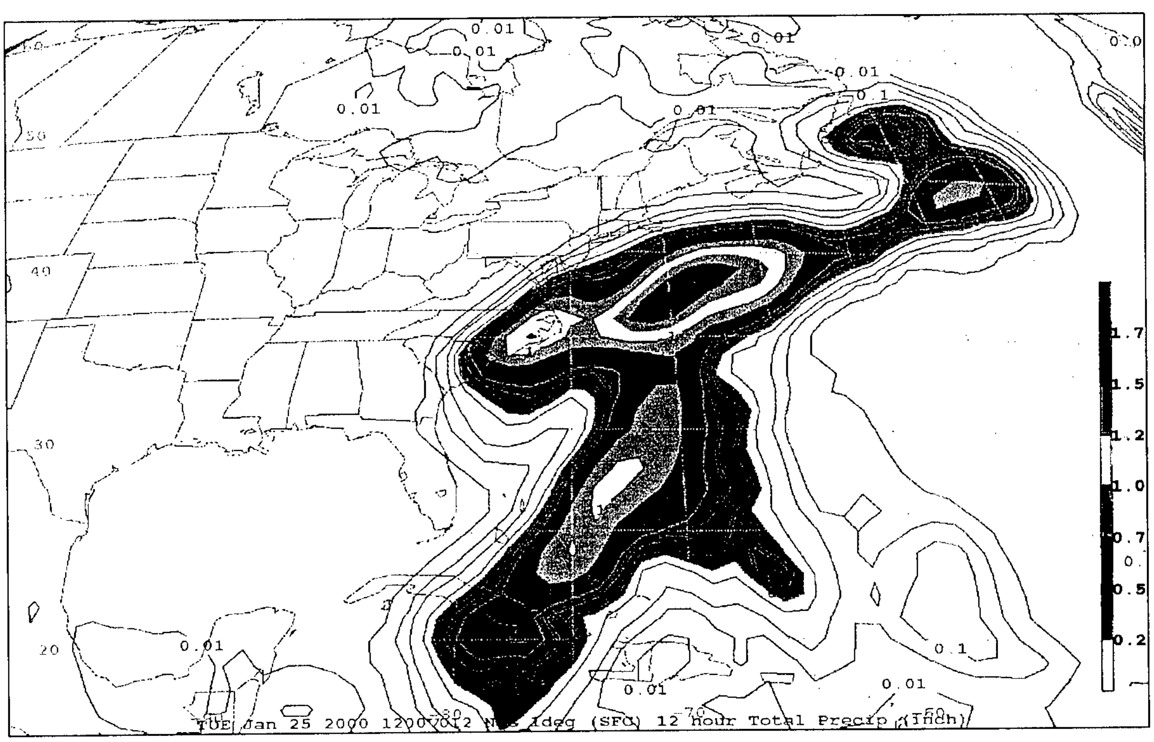


Figure 4.11. NOGAPS 12-Hour Precipitation Forecast from the 25/00 Run, Valid at 25/12.

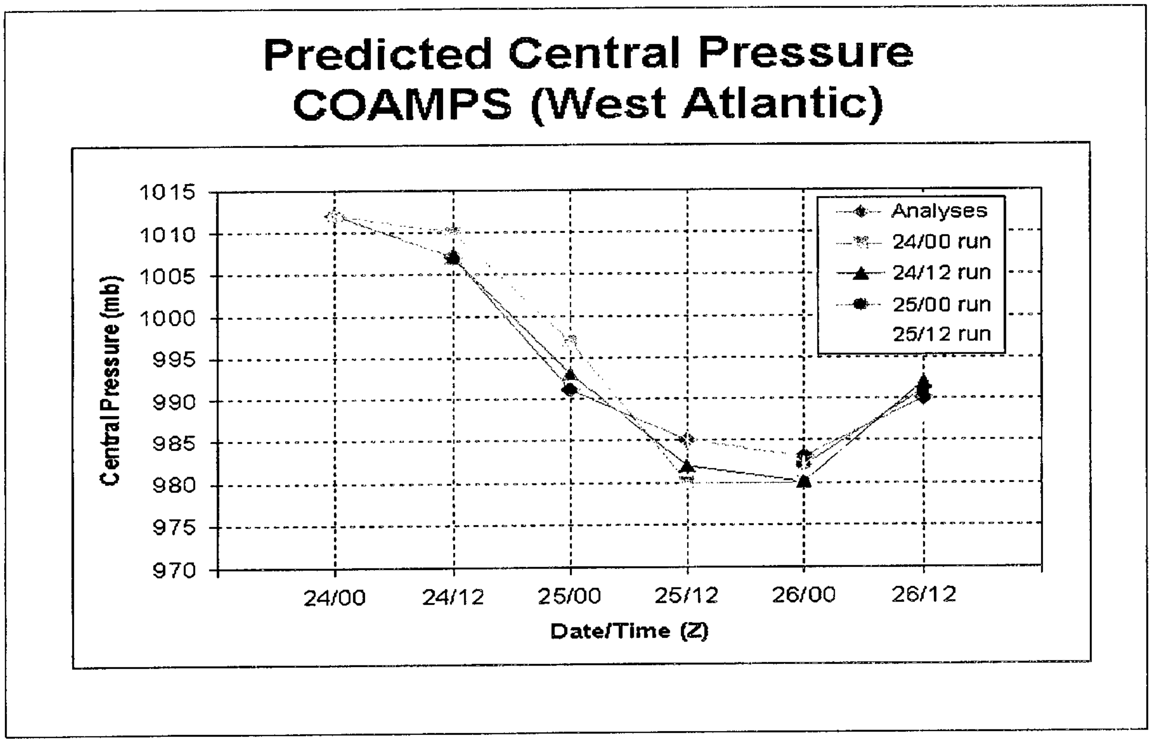
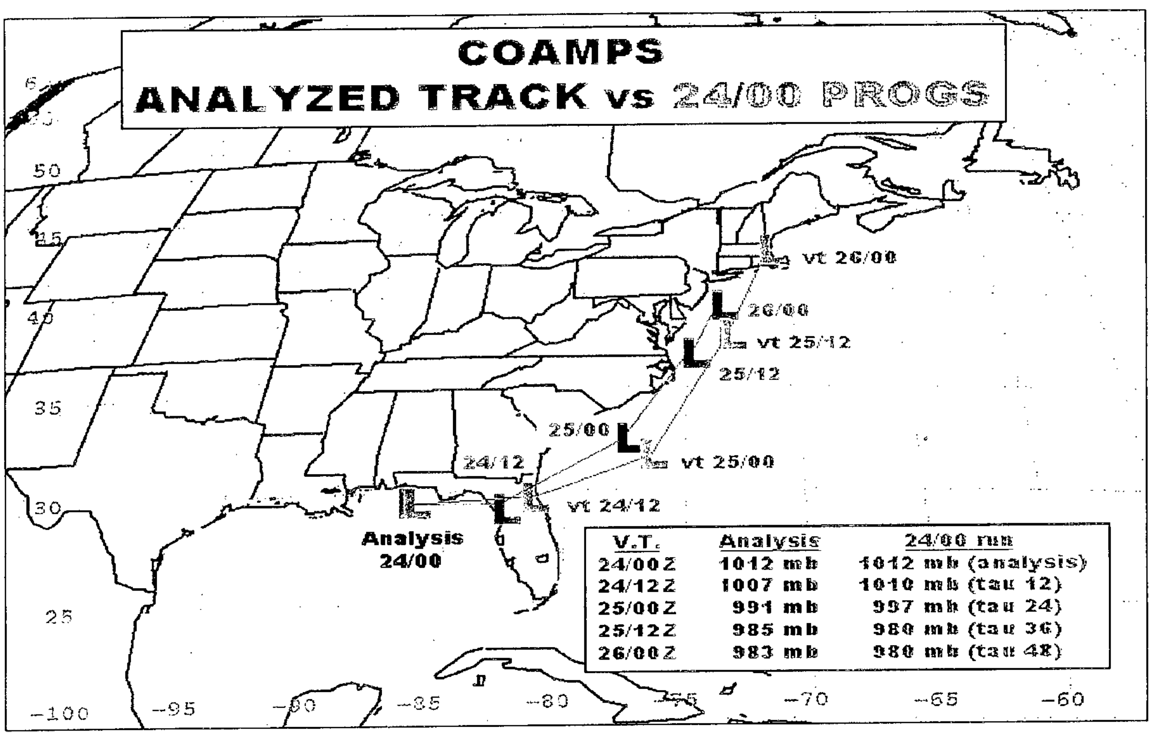


Figure 4.12. COAMPS (West Atlantic) Forecast Central Pressure.



V.T.	Analysis	24/00 run
24/00Z	1012 mb	1012 mb (analysis)
24/12Z	1007 mb	1010 mb (tau 12)
25/00Z	991 mb	997 mb (tau 24)
25/12Z	985 mb	980 mb (tau 36)
26/00Z	983 mb	980 mb (tau 48)

Figure 4.13. COAMPS Analyzed Track and 24/00 Run.

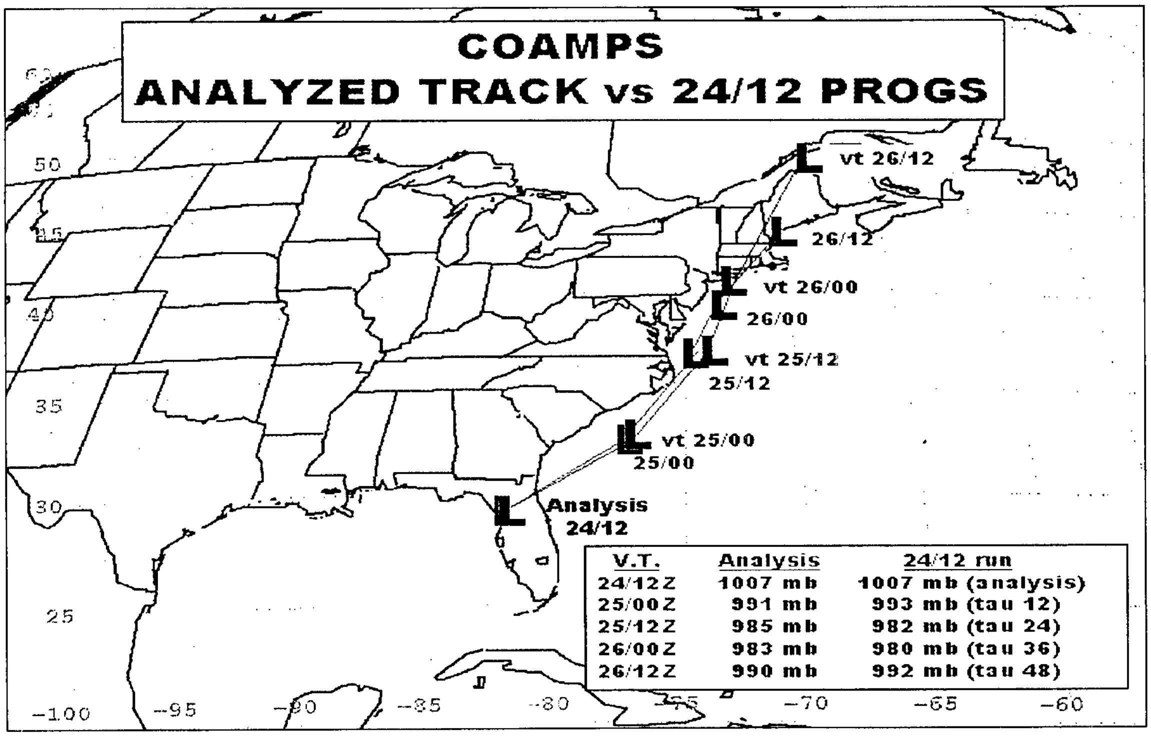


Figure 4.14. COAMPS Analyzed Track and 24/12 Run.

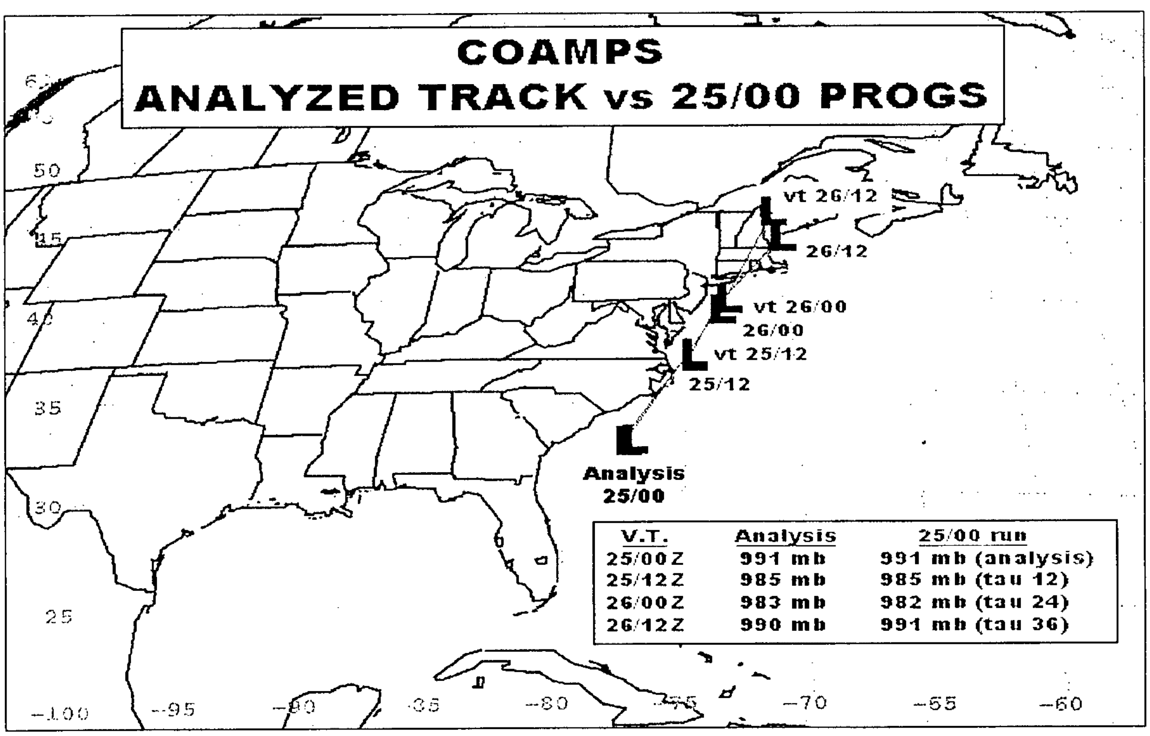


Figure 4.15. COAMPS Analyzed Track and 25/00 Run.

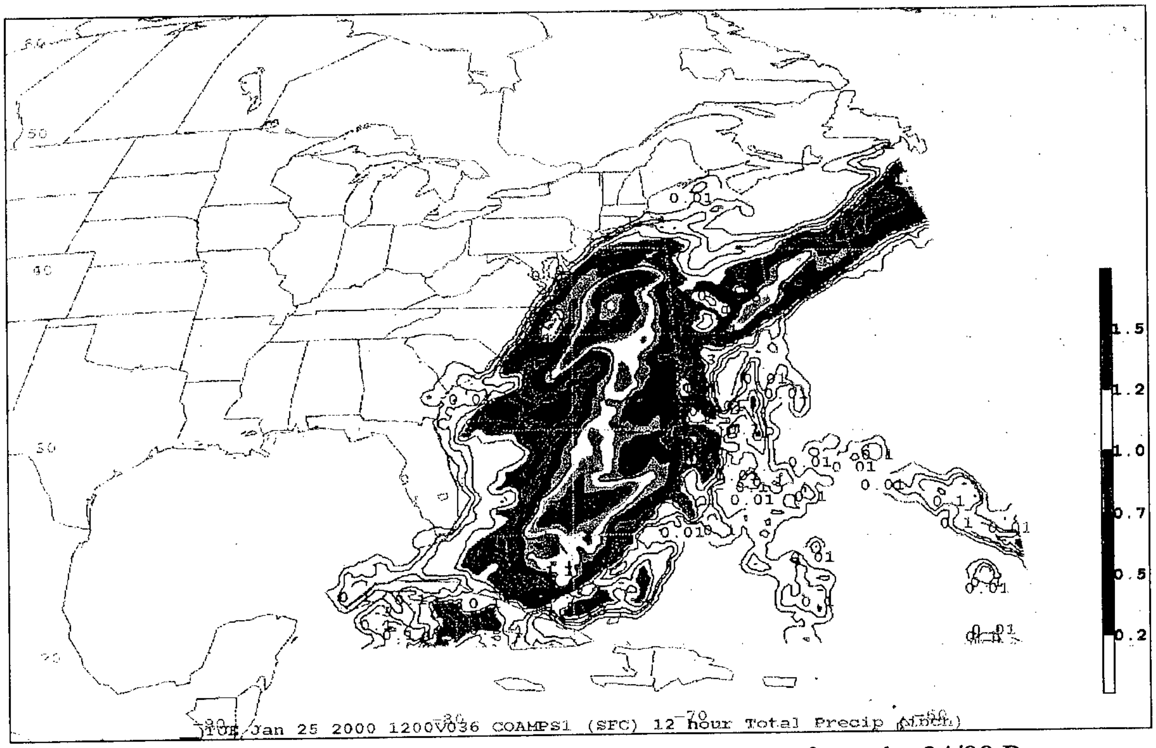


Figure 4.16. COAMPS 36-Hour Precipitation Forecast from the 24/00 Run, Valid at 25/12

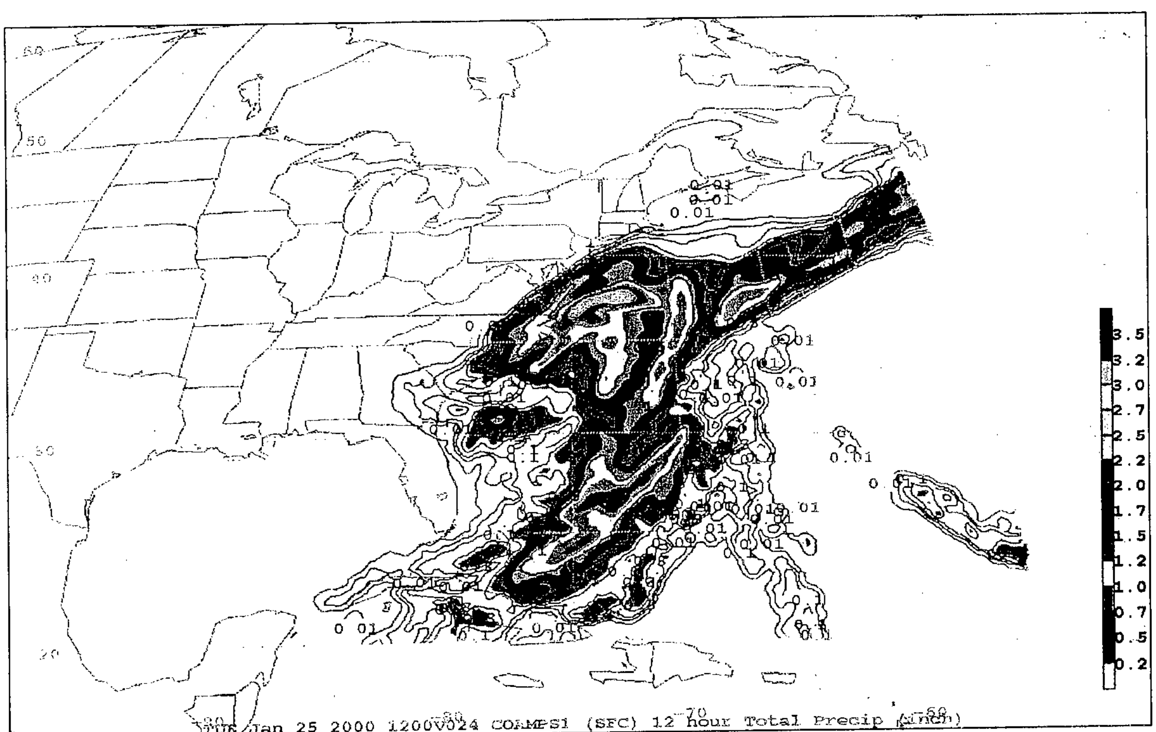


Figure 4.17. COAMPS 24-Hour Precipitation Forecast from the 24/12 Run, Valid at 25/12

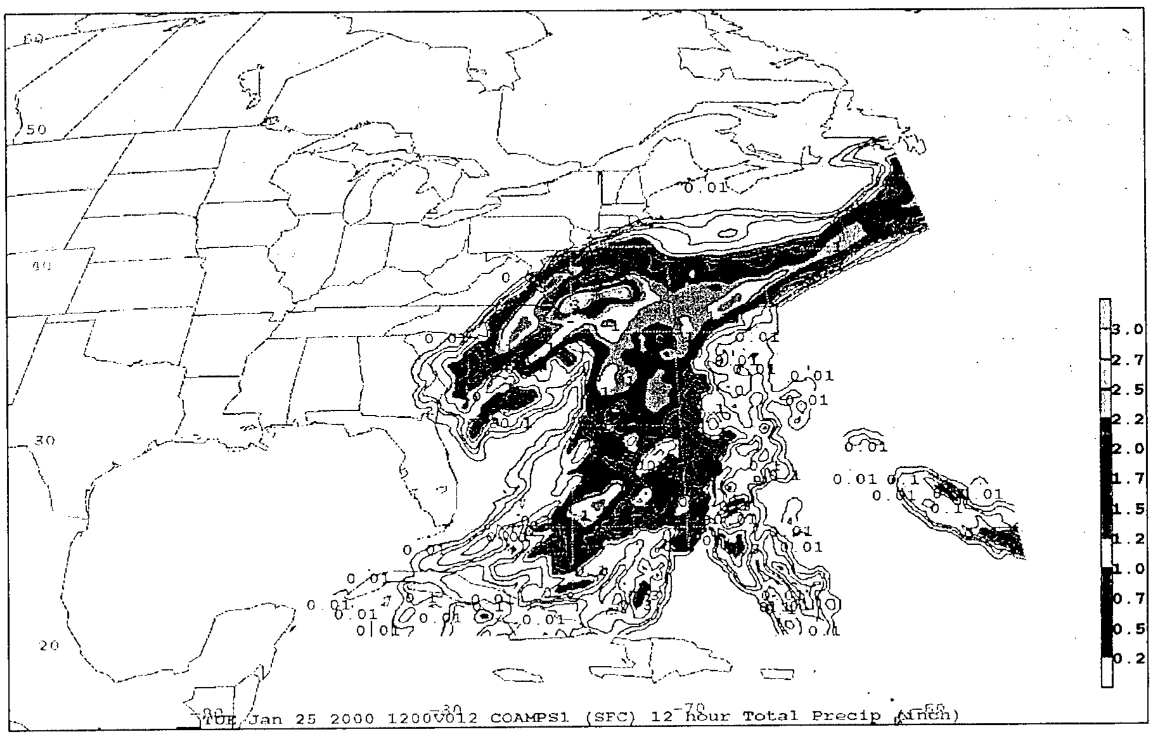


Figure 4.18. COAMPS 12-Hour Precipitation Forecast from the 25/00 Run, Valid at 25/12

THIS PAGE INTENTIONALLY LEFT BLANK

V. UPPER-LEVEL AND COASTAL FRONT EVALUATION

To explore reasons for model errors in this major cyclogenesis event, NOGAPS and COAMPS analysis and forecast errors are evaluated. In this chapter, we will verify 500 mb height fields and 250 mb isotachs, and then explore evidence of coastal frontogenesis.

A. NOGAPS 500 MB FORECAST HEIGHT ERRORS

1. 500 mb Height Forecasts for Valid Time 25/00

The 24 h forecast from the 24/00 run is very poor for the US East Coast (Fig. 5.1). It fails to develop the cutoff low, forecasting only an open wave structure at 500 mb. The forecast trough is 60 meters too shallow and too wide across, while the predicted downstream ridge is 60 meters too low. The forecast tilt is neutral to slightly positive, not negative as analyzed, which gives the resulting forecast pattern improper downstream curvature and a weaker diffluent region.

Even the 12 h forecast from the 24/12 run fails to resolve the cutoff low (Fig. 5.2) and shows the same deficiencies. The base of the trough is 40 meters too shallow and the downstream ridge is 30 meters too weak. Although NOGAPS is successfully deepening the sea-level cyclone (Chapter IV), it is deficient in forecasting mid-troposphere development.

2. 500 mb Height Forecasts for Valid Time 25/12

The short range forecasts for 25/12 are also unsatisfactory. The 36 h 500 mb height forecast from the 24/00 run (Fig. 5.3) shows only a small amplitude short wave trough instead of the 500 mb cutoff low. This forecast short wave is placed too far east

and has an amplitude error of 80 meters in the trough (too shallow) and 80 meters in the downstream ridge (too low). Similar errors are found in the 24 h forecast from 24/12 (Fig. 5.4). It is important to note the NOGAPS analysis itself does not resolve the full trough/ridge amplification, and so these forecasts are actually even worse when compared to sounding data.

B. COAMPS 500 MB FORECAST HEIGHT ERRORS

1. 500 mb Height Forecasts for Valid Time 25/00

Similar deficiencies in mid-tropospheric forecasts are found in COAMPS also. The 24 h 500 mb forecast from the 24/00 run is disappointing, with a wave structure that is very different from the verifying analysis (Fig. 5.5). The forecast fails to develop the cutoff low and only shows a very narrow, positively tilted, short wave trough. In addition to the poor trough forecast, the downstream ridge is under-developed, with large errors in the curvature of the flow. The trough is 20 to 30 meters too shallow, and the ridge is 30 to 40 meters too low. These heights errors reflect the incorrectly forecast wave structure.

Figure 5.6 shows improvement in the 12 h forecast from the 24/12 run. The cutoff low is forecast, although it is too small. The upstream ridge is forecast only 10 to 20 meters too low, and the downstream ridge is 20 meters too low over Maryland. The COAMPS forecast does try to smooth the downstream ridge, which results in these height errors. The net result is slightly insufficient downstream curvature of the flow.

2. 500 mb Height Forecasts for Valid Time 25/12

The 36 h forecast from the 24/00 run is a surprisingly better forecast considering how poorly the 24 h forecast from 24/00 verified. Figure 5.7 shows the cutoff low is missed, but the forecast is attempting to build the downstream ridge. The trough is 40

meters too shallow, and the downstream ridge is 40 meters too low, but the wave structure is close to analysis despite the lack of a 500 mb cutoff.

The 24 h forecast from the 24/12 run (Fig. 5.8) attempts to close off a cutoff low. A more significant error in this forecast is that the trough is placed to the northeast of the analyzed position. This in turn affects the downstream ridge placement. The height fields do not have significant amplitude error in them, but the trough/ridge system is placed too far to the northeast. In general the COAMPS 500 mb forecasts are more successful than NOGAPS, particularly the 24/12 run. Recall the surface low forecasts from the 24/12 run were very accurate (Fig. 4.14), and this COAMPS run also predicted intense precipitation ahead of the cyclone (Fig. 4.17).

C. NOGAPS 250 MB ISOTACH ANALYSIS ERRORS

Jet streak errors are also evident in the short range forecasts. This cyclone is characterized by two intense 250 mb jet streaks, here referred to as the "upstream" jet streak and the "downstream" jet streak. The analysis deficiencies will be discussed in this section and forecast errors in the next section.

At 24/00, the downstream jet streak analysis differs from a number of the East Coast soundings. The soundings suggest the analysis has too weak of a jet core and should extend further to the south (Fig. 5.9). Specific examples are Albany, NY is analyzed 20 kt too weak, Roanoke, VA is 10 kt too weak, and Peachtree City, GA indicates 100 kt wind but is well outside the 100 kt isotach. NOGAPS also under-analyzes the high-speed jet core of the upstream jet. Although there is no 140 kt isotach analyzed, two stations (Amarillo and Midland) are reporting 140 kt or more.

Again at 24/12, the downstream jet core is too weak and does not extend far enough south (Fig. 5.10). The 140 to 150 kt soundings from Brookhaven, NY to Yarmouth, Canada are not fully reflected in the analysis that only indicates a 130 kt max. To the south, the model's 100 kt isotach extends only into northeast North Carolina, where soundings show 100 to 120 kt winds extending into South Carolina and Georgia. The actual jet acceleration region is much smaller than the model analysis, which has a large negative impact on the analysis of upper-level divergence. The 250 mb upstream jet is placed well, but also has intensity errors. The core of the jet streak over Texas is indicated too weak by up to 20 kt. The soundings further suggest that there is more horizontal shear in the left exit region over Louisiana and Mississippi than the analysis shows.

Moving to 25/00, the 250 mb downstream jet streak is placed too far east (Fig. 5.11). The model analysis misses the 95 to 110 kt winds over central Virginia and central North Carolina. The acceleration region (some 60 knots based on the soundings) is from South Carolina to North Carolina but is not resolved in the wind analysis. Again, the upstream jet speeds are not high enough. The forecast max isotach is 150 kt, where 155 to 175 kt winds are indicated over Missouri, Kansas, and Nebraska.

At 25/12, the southern extension of the 250 mb downstream jet streak is placed over the western Atlantic, so there is no sounding data to verify the winds (Fig. 5.12). However, overland soundings suggest that this jet streak placement is questionable and may be too far east of the actual position. The Wallops Island, MD sounding shows 95 kt, but the analysis reflects only a 60 kt isotach with the higher wind speeds to the east of this position. Also, Brookhaven, NY indicates a 110 kt sounding compared to the

NOGAPS analysis of 90 to 100 knots. The isotach pattern appears satisfactory but if it were shifted further to the west it would match the soundings better. The upstream jet continues to be poorly analyzed. The analysis correctly shows a 160 kt max, but the 150 kt isotach should cover a larger region and extend east over Mississippi.

D. NOGAPS 250 MB FORECAST ISOTACH ERRORS

This section will investigate 250 mb isotach forecast errors for valid times of 25/00 and 25/12 from the 24/00 and 24/12 runs. Only the 250 mb level is chosen as it best reflects the jet streaks of this storm. In addition, most of the wind analysis errors are at this level.

Figure 5.13 shows that the 24 h forecast from the 24/00 run (valid at 25/00) fails to predict the high winds through central Virginia and North Carolina and shows deficiency in the acceleration region. However, the intensity of the jet core is properly forecast, with a 140 kt isotach max comparing to the 150 kt sounding from Yarmouth, Canada. The upstream jet streak is quite different, with forecast winds over Kansas and Nebraska weak by as much as 40 kt (see Fig. 5.11).

The 12 h forecast from the 24/12 run (valid at 25/00) has stretched the downstream jet core, but has weakened the intensity, predicting only a 120 kt isotach max (Fig. 5.14). The high wind speeds over central Virginia and North Carolina are also not forecast. The upstream jet streak winds remain under-forecast, but some improvement is evident. The isotach max is 150 kt, compared to sounding values up to 175 kt.

The 36 h forecast from the 24/00 run (valid at 25/12) places the downstream jet too far east (Fig. 5.15), which is consistent with the poor height forecast for this time.

The upstream jet streak is located well, but the core is 10 to 20 kt weak compared to soundings from Jackson, MS and Key West, FL.

The 24 h forecast from the 24/12 run (Fig. 5.16) also places the downstream jet streak too far east, but some improvement is seen from the 36 h forecast from 24/00. There are no soundings over the western Atlantic to verify wind speeds, but data along the coast shows under-forecast speeds. Improvement is also seen in the upstream jet, but the predicted winds in the jet core are 10 kt weak from Jackson, MS to Key West, FL.

E. COAMPS 250 MB ISOTACH ANALYSIS ERRORS

The COAMPS upper-level isotach analyses are able to capture more small scale variation than NOGAPS due to the higher resolution. This is most evident with the 25/00 analysis of the downstream jet streak. While COAMPS has higher resolution, the analyses are not necessarily better than NOGAPS. The 250 mb isotach analyses do contain errors that are addressed in this section.

Serious wind analysis errors are occurring at 24/00 (Fig. 5.17). The COAMPS analysis max is 140 kt near Yarmouth, Canada where the sounding shows 150 kt. The 130 kt isotach should extend further to the south to include Roanoke, VA, as well as the 100 kt isotach extending to reach Peachtree City, GA. The failure to extend the 100 through 130 kt isotachs far enough south degrades the analysis of the jet entrance region. The grid domain does not extend far enough west to see the upstream jet streak.

The 24/12 250 mb analysis (Fig. 5.18) has problems similar to those in the 24/00 analysis. The Yarmouth sounding continues to show 150 kt, but the model max is only 130 kt in that area. The 100 and 120 kt isotachs should extend further to the south and overlie Georgia. As a result, the analysis of the jet entrance region over Georgia and

Florida is poor. While these deficiencies exist in the COAMPS analysis, it is important to note that COAMPS does show a longer jet core than NOGAPS (see Fig. 5.10), which agrees more closely with sounding data. The grid domain does not go far enough to the west to see the upstream jet streak.

There is no sounding data at 25/00 to verify the placement of the jet max east of Virginia and North Carolina (Fig. 5.19). Soundings do suggest the 120 kt isotach should cover a larger area, but the ability of the COAMPS analysis to get a 120 kt isotach is an improvement over NOGAPS for this region. However, weak areas are present in the COAMPS analysis. The wind speeds off of New England are considerably stronger with NOGAPS, but no sounding data are available for verification. Additionally, the Greensboro, NC sounding shows 95 kt, while the COAMPS analysis is less than 60 kt, indicating the acceleration zone is misplaced to the east. The upstream jet streak is coming into the model domain. Soundings show that the jet core is too weak, but this is at the western boundary blend zone, and NOGAPS was weak in this area also.

At 25/12, the southern extension of the 250 mb jet streak off the East Coast seems to be placed too far east, but no over water soundings are available to verify this (Fig. 5.20). The Wallops Island sounding is 95 kt, while the analysis is less than 60 kt near there. Other than the placement of the jet streak, the analysis is good. The upstream jet streak is only slightly weaker than observed, with departures of 5 knots. The model seems to capture this upstream jet streak well.

F. COAMPS 250 MB FORECAST ISOTACH ERRORS

Following the NOGAPS model, this section will investigate 250 mb isotach forecast errors for valid times of 25/00 and 25/12 from the 24/00 and 24/12 runs. As

noted with the 250 mb isotach analysis discussion in the last section, the COAMPS forecasts also show more small scale variability than NOGAPS due to the higher resolution.

The 24 h forecast from the 24/00 run (Fig. 5.21) shows the southern extension of the downstream jet max winds are 20 to 30 kt weaker and are placed further east than the sounding data (compare with Fig. 5.19). The high wind speeds over Washington DC, Roanoke, VA and Greensboro, NC are not forecast. The upstream jet seems reasonable, but the wind speeds are slightly weak over Little Rock, AR.

The 12 h forecast from the 24/12 run (valid at 25/00) does better with the downstream jet streak (Fig. 5.22), but it is still slightly weak and placed too far east (compare with Fig. 5.19). As a result, the high wind speed over Greensboro, NC and Roanoke, VA are not properly forecast. The upstream jet streak verifies well.

No sounding data is available in the western Atlantic to verify the placement of the southern extension of the jet streak from the 36 h forecast from the 24/00 run (valid at 25/12). However, Fig. 5.23 shows weak forecast winds from Brookhaven, NY to Wallops Island, MD, suggesting the forecast placement is too far east (compare with Fig. 5.20). The upstream jet streak also forecasts wind speeds that are 10 to 20 kt too low over Jackson, MS and Key West, FL. Figure 5.24 shows the 24 h forecast from 24/12 (valid at 25/12) has similar errors.

G. COASTAL FRONT

Synoptic surface analysis (Fig 3.4 and 3.9) suggests conditions are favorable for a coastal frontal development. A manual analysis (Fig. 5.25 through 5.34) using airport observations, ship reports, and buoy data shows a strong coastal front is evident at 23/06

(Fig. 5.26). A 7° C/30 km gradient is found off the South Carolina coast with a 5° C/30 km gradient off Cape Hatteras. By 23/12, the front off Cape Hatteras has a 10° C/30 km gradient (Fig. 5.27).

The coastal front shows diurnal variation, as it is weakest during the day when the land heats faster than the air over the water. By 24/12, the coastal front is most intense along the North Carolina coast (7° C/30 km) (Fig. 5.31). The front remains over Cape Hatteras through 25/00 (Fig. 5.33). As seen in Chapters III and IV, the cyclone passed over Cape Hatteras at 25/06. The strong coastal front provides enhanced low-level baroclinicity and is a factor in the cyclone's coastal path.

With such a sharp coastal front, it is reasonable to assume that a model would require higher horizontal resolution to resolve it. The following sections discuss NOGAPS and COAMPS analyses and forecasts of the 2-meter model temperatures focused on the coastal front region.

H. NOGAPS ANALYSIS OF THE COASTAL FRONT

The 24/00 analysis (Fig. 5.35) misplaces the 0° isotherm to the north. The NOGAPS analysis places the 2° isotherm through North Carolina, where surface observations indicate 0° and even -1° C. However, the shape of the 2° isotherm does indicate weak cold air damming. Temperature errors exist along the North Carolina coast, where the model places the 12° isotherm and data shows that 8° is more accurate. In general, the NOGAPS analysis only resolves a weaker temperature gradient along the coast.

By the 24/12 analysis (Fig. 5.36), the 0° isotherm shows better placement through North Carolina. However, the positive isotherms to the south indicate too weak a gradient. The temperature along the coast is analyzed at 8° to 10°, where data shows the true temperature to be closer to 4°. Continuing offshore, the analysis shows a weaker temperature gradient and does not indicate the sharpness of the true front.

The 25/00 analysis (Fig. 5.37) places the 0° isotherm well, but poorly represents the other overland temperatures. The coastal temperature gradient is too weak. A 5° temperature error also exists at Cape Hatteras when compared with the temperature reading from the near by Diamond Shoals Light buoy.

I. NOGAPS FORECASTS OF THE COASTAL FRONT

As would be expected, the NOGAPS global model, with about 100 km horizontal resolution, poorly forecasts the coastal front. NOGAPS shows problems forecasting the cold temperatures and the cold air damming through Virginia and North Carolina. Twelve and 24 h forecasts resolve only weak temperature gradients along the coast. One example (not shown) is the 24 h forecast from the 24/00 run (valid at 25/00), where only a 1° to 2° C/30 km gradient is predicted.

J. COAMPS ANALYSIS OF THE COASTAL FRONT

In comparison to NOGAPS, the COAMPS analyses are much better. Figure 5.38 shows the COAMPS 24/00 analysis satisfactorily places the 0° isotherm and the cold air damming. The coastal temperatures are analyzed well and the temperature gradient of the coastal front is good. The gradient over Cape Hatteras is slightly weak, but in general this is a good analysis of the intense coastal front.

Figure 5.39 shows the 24/12 analysis to be less successful. Cold air damming is evident, but the analysis land temperatures are too cold. As a result, the 0° isotherm is placed too far to the south. A temperature gradient is shown along the coast, but it is too weak along North Carolina. The frontal structure is definitely present however.

The below freezing analyzed temperatures over land on the 25/00 analysis are 2° to 4° too cold compared to observations (Fig. 5.40). The 0° isotherm is moved too far into eastern Virginia. The frontal structure is clearly shown, but it is slightly weak along the South Carolina coast. The model places a 12° isotherm over Cape Hatteras, while the near by Diamond Shoals Light buoy reports 7°. This 5° error makes the model temperature gradient too weak over Cape Hatteras, although this analysis is still much better than NOGAPS.

K. COAMPS FORECAST OF THE COASTAL FRONT

As was the case with the surface temperature analyses, the forecasts predict land temperatures that are too cold. The 24 h forecast from 24/00 (Figure 5.41) shows the temperatures through Virginia and North Carolina to be up to 6° too cold. This moves the 0° isotherm too far south. The temperatures along the coast are within 2° of the analysis, but the offshore gradient is weaker. The forecast exhibits frontal structure, but it is weaker than the analysis. The 12 h forecast from 24/12 (Fig. 5.42) shows the same problem with the overland cold temperatures. The 0° isotherm is too far to the south and east. This makes the temperatures along the coast about 2° too low, but the frontal structure is present. This forecast has basically the same temperature gradient as the verifying analysis.

L. SUMMARY

The verification revealed both COAMPS and particularly NOGAPS failed to properly amplify the short wave upper-level ridge immediately downstream of the development. This caused the short wave trough to be underdeveloped, even in the short range forecasts. The consequence of these errors was upper-level forecasts that did not capture the diffluent flow and negative (southeast to northwest) tilt of the rapidly growing short wave. Forecast flow was placed too far east, related to the poor forecast cyclone tracks.

Manual surface temperature analysis revealed the presence of an intense coastal front. With higher horizontal resolution, COAMPS was more successful at analyzing and forecasting the front than NOGAPS. This allowed COAMPS to develop a more enhanced low-level baroclinic zone along the coast than NOGAPS, which aided better storm track forecasts.

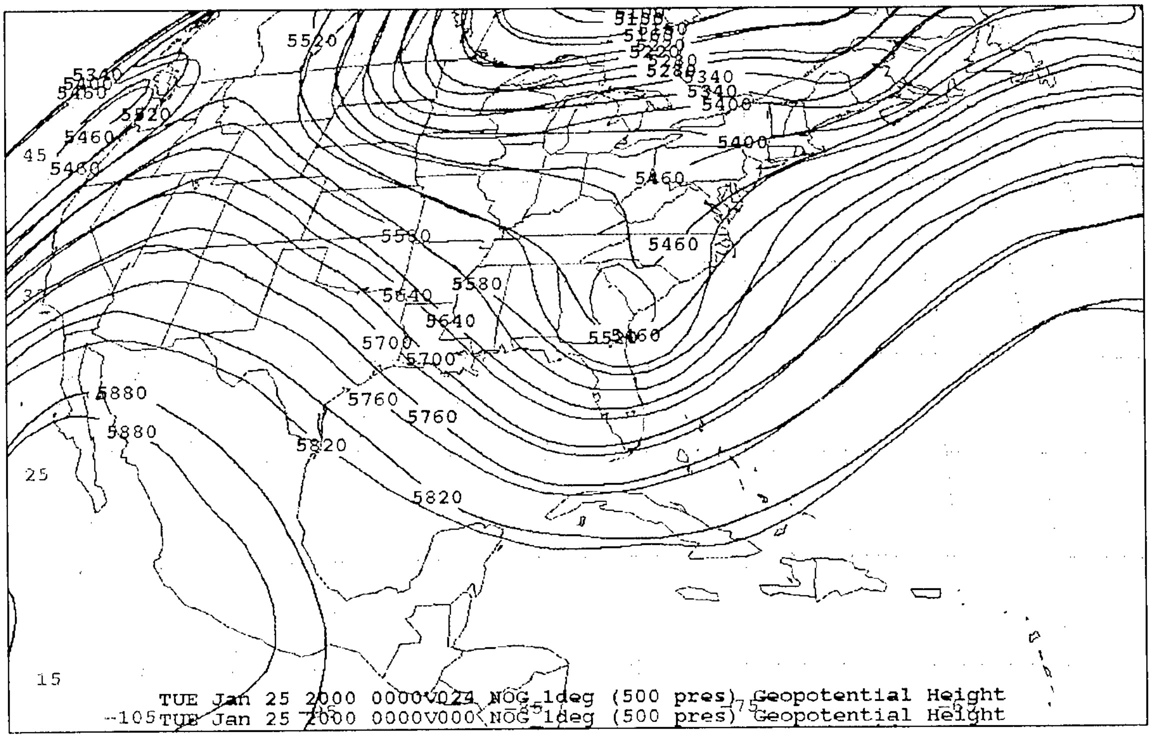


Figure 5.1. NOGAPS 500 mb Heights, 25/00 Analysis and the 24-Hour Forecast from the 24/00 Run, Valid at 25/00.

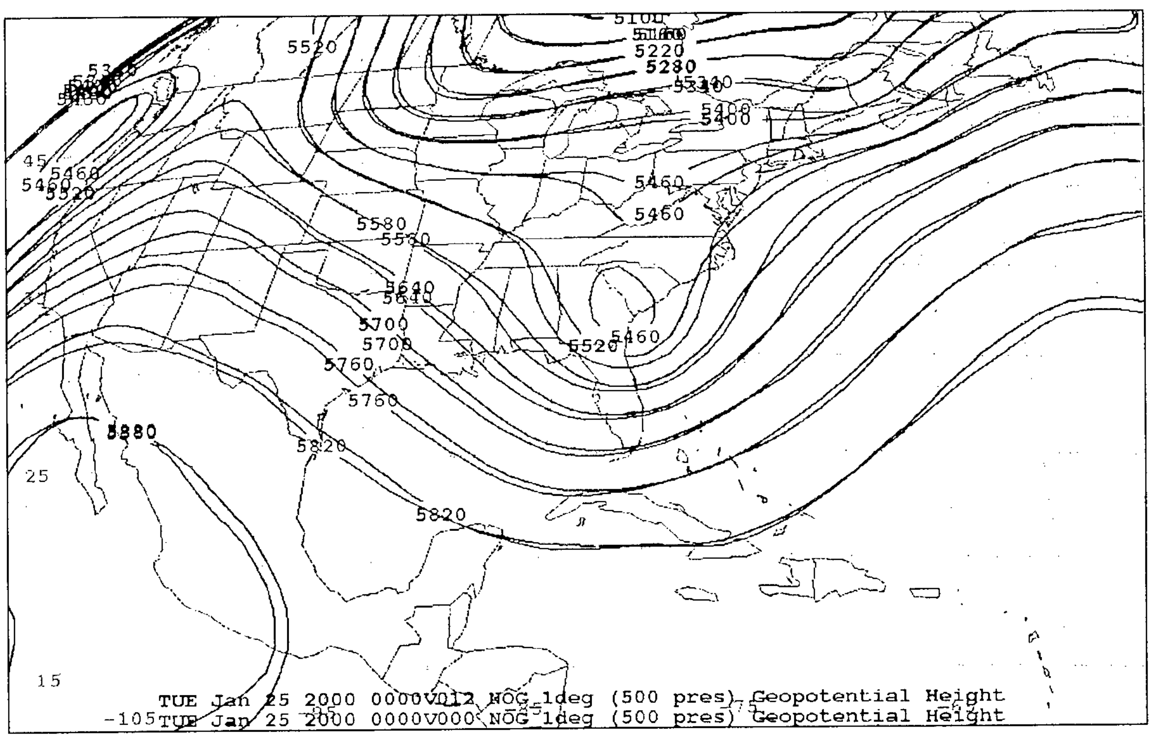


Figure 5.2. NOGAPS 500 mb Heights, 25/00 Analysis and the 12-Hour Forecast from the 24/12 Run, Valid at 25/00.

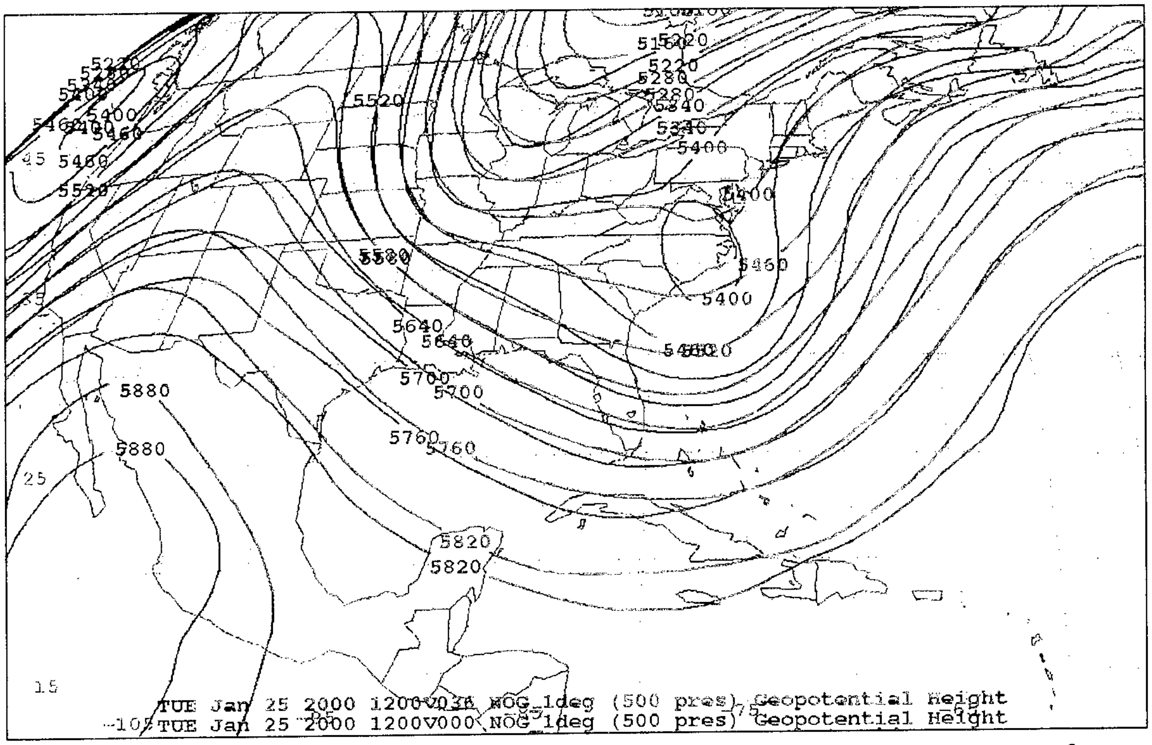


Figure 5.3. NOGAPS 500 mb Heights, 25/12 Analysis and the 36-Hour Forecast from the 24/00 Run, Valid at 25/12.

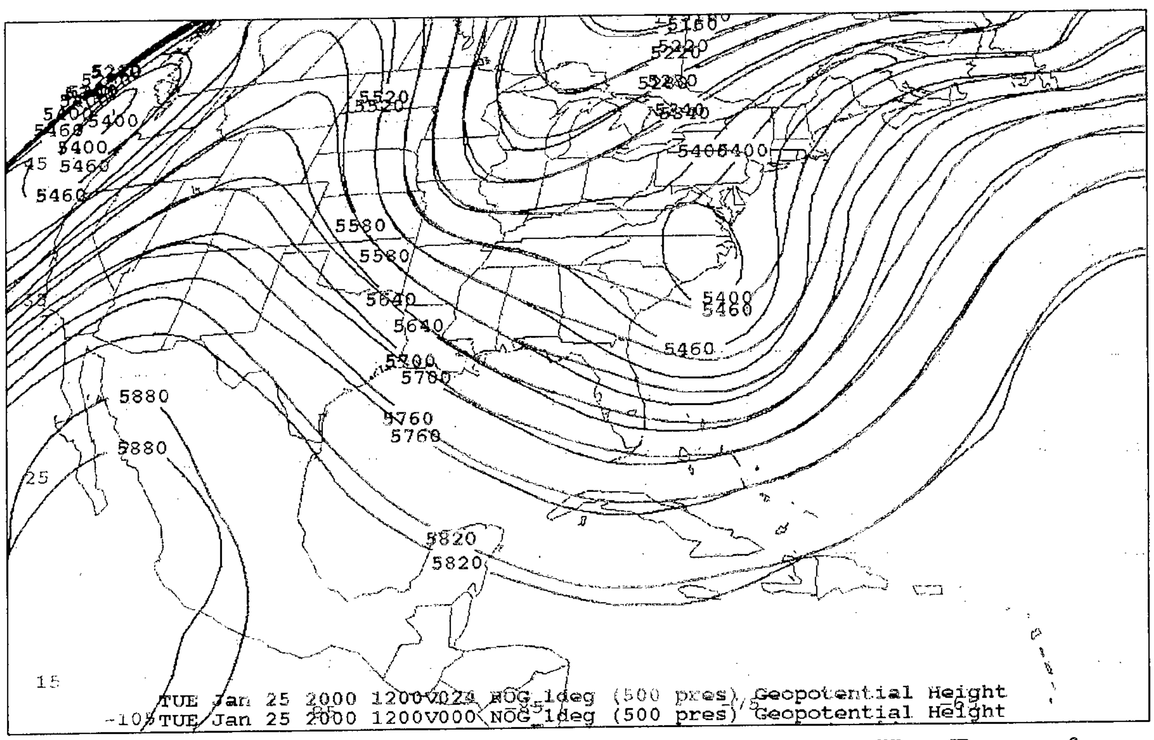


Figure 5.4. NOGAPS 500 mb Heights, 25/12 Analysis and the 24-Hour Forecast from the 24/12 Run, Valid at 25/12.

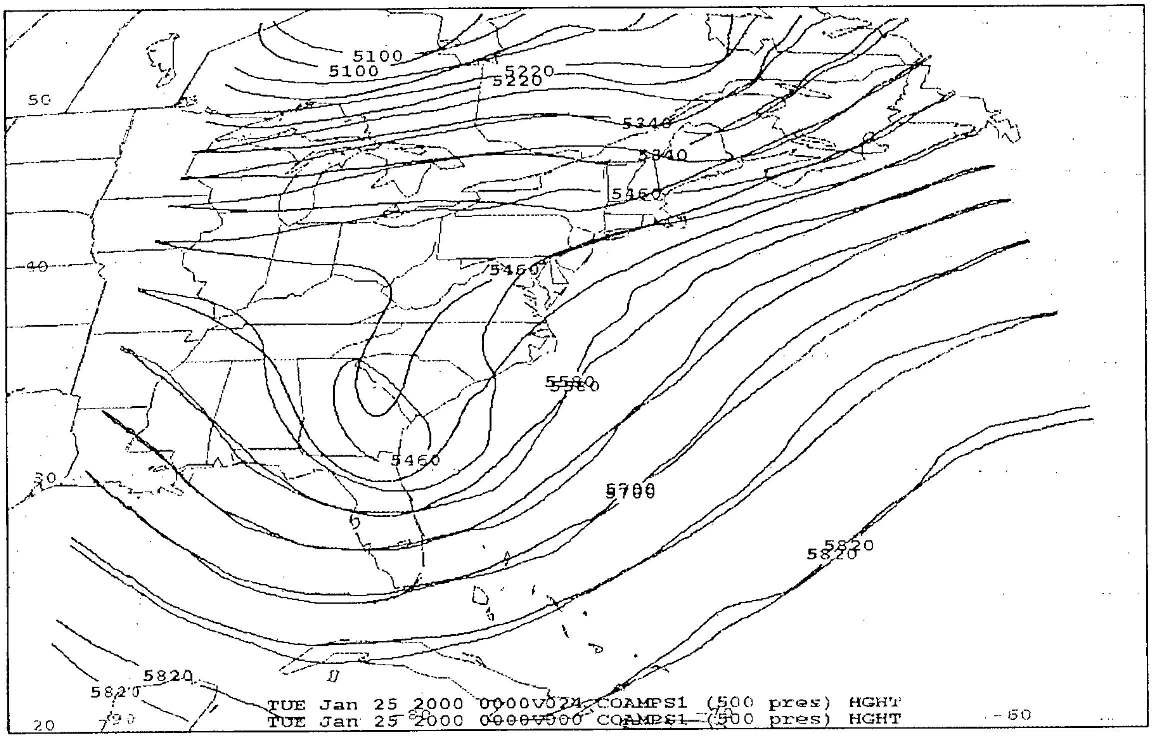


Figure 5.5. COAMPS 500 mb Heights, 25/00 Analysis and the 24-Hour Forecast from the 24/00 Run, Valid at 25/00.

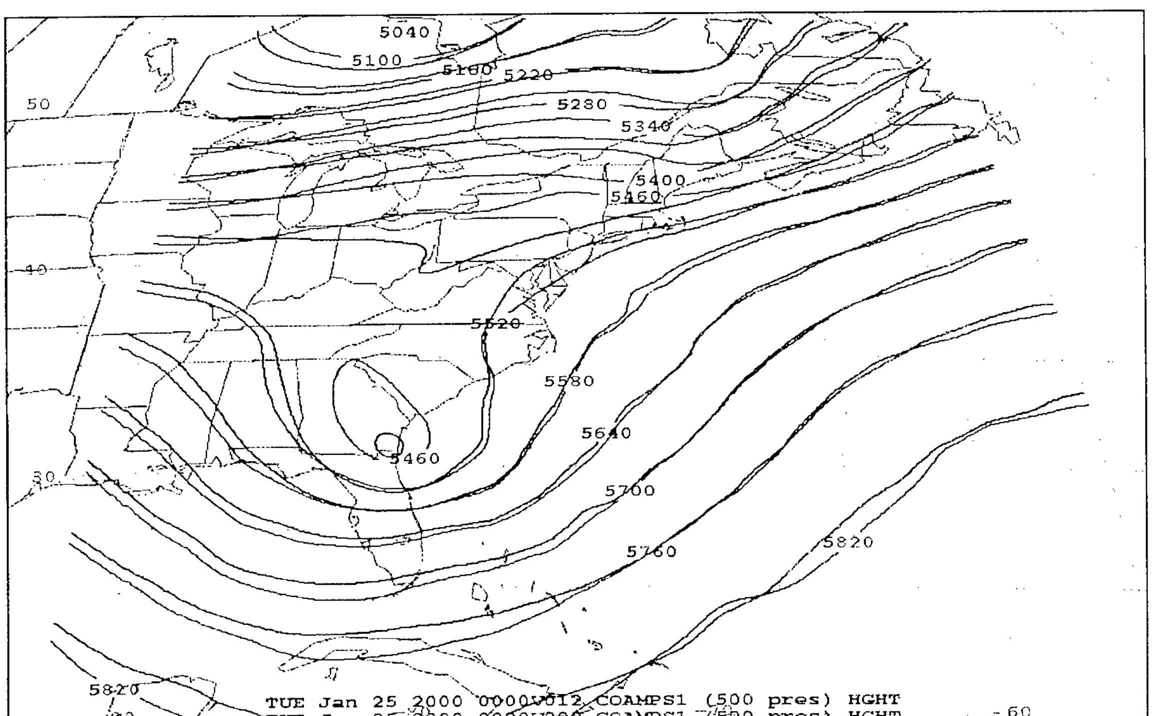


Figure 5.6. COAMPS 500 mb Heights, 25/00 Analysis and the 12-Hour Forecast from the 24/12 Run, Valid at 25/00.

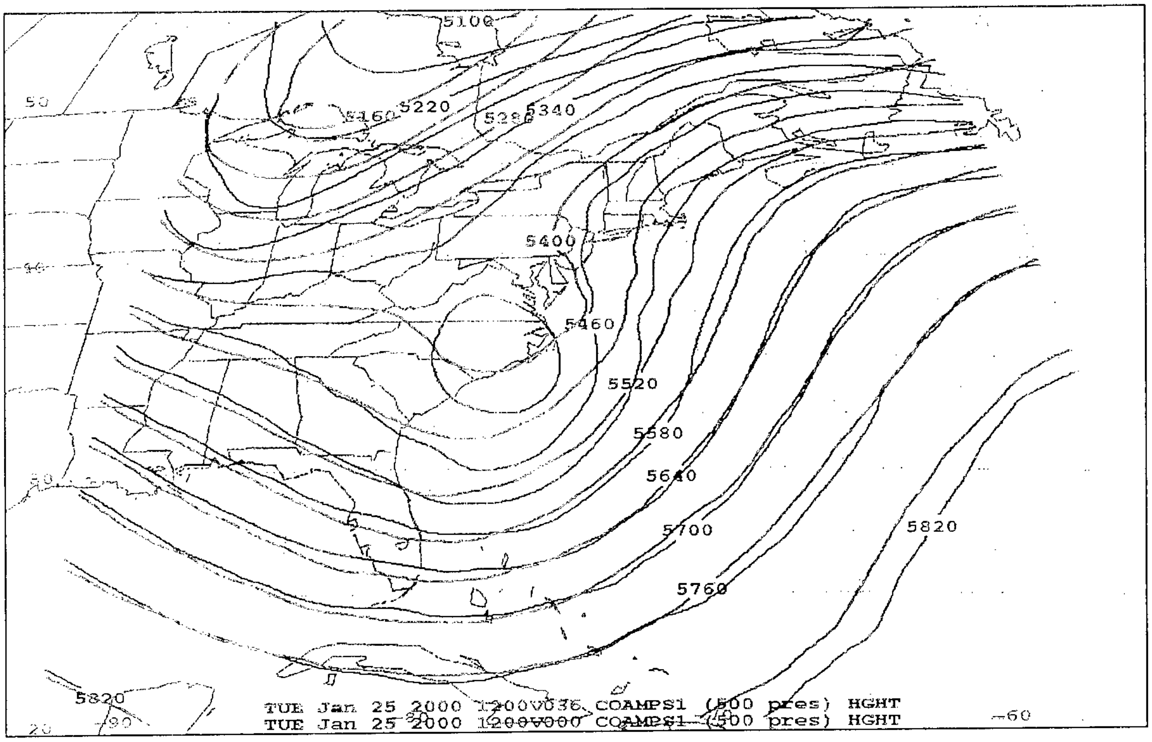


Figure 5.7. COAMPS 500 mb Heights, 25/12 Analysis and the 36-Hour Forecast from the 24/00 Run, Valid at 25/12.

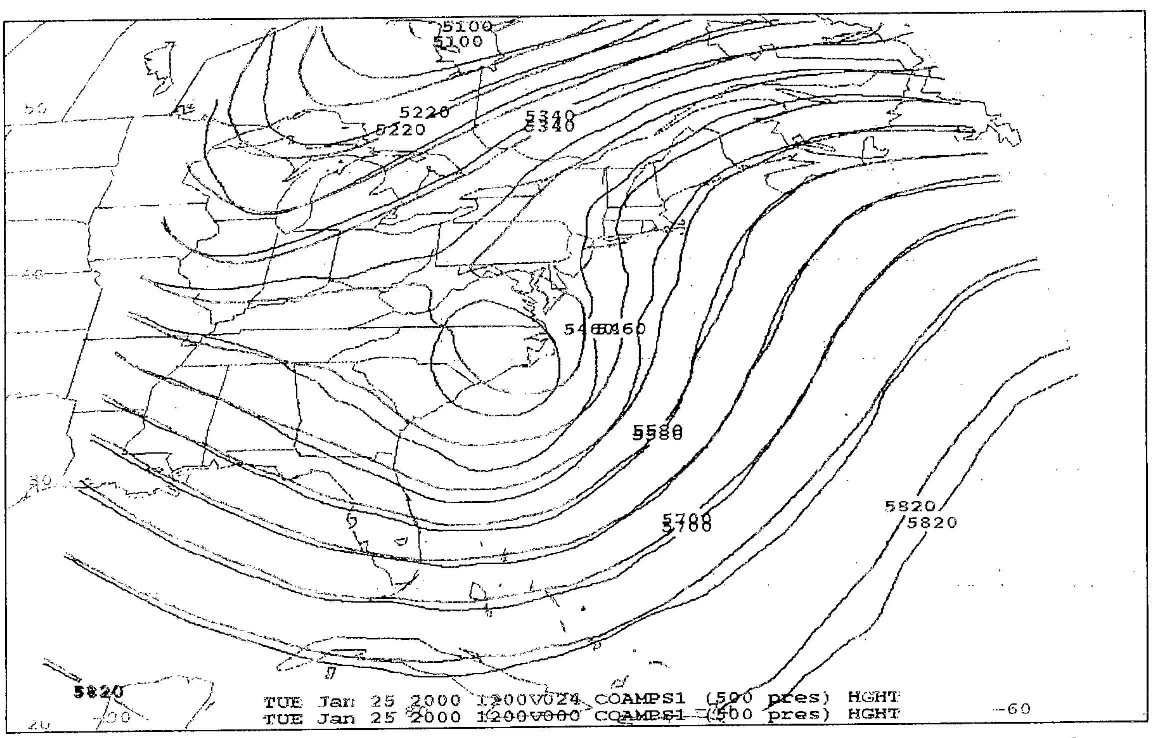


Figure 5.8. COAMPS 500 mb Heights, 25/12 Analysis and the 24-Hour Forecast from the 24/12 Run, Valid at 25/12.

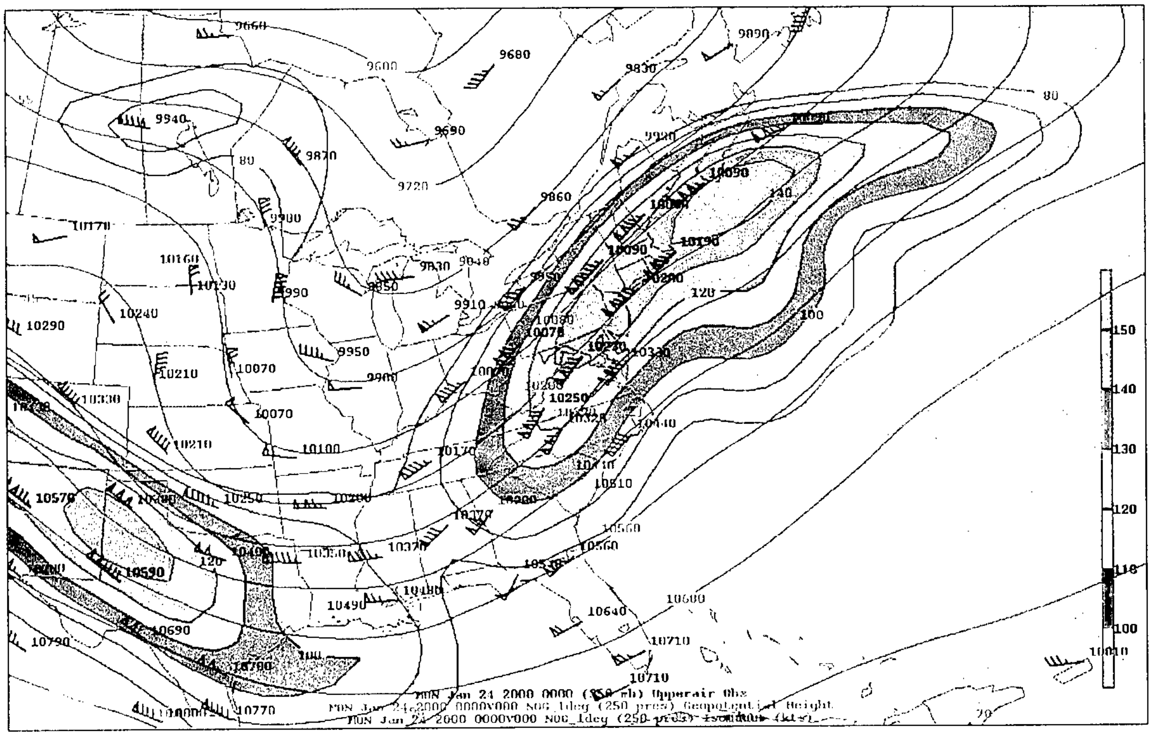


Figure 5.9. NOGAPS 250 mb Heights and Isotachs from the 24/00 Analysis, with Sounding Data.

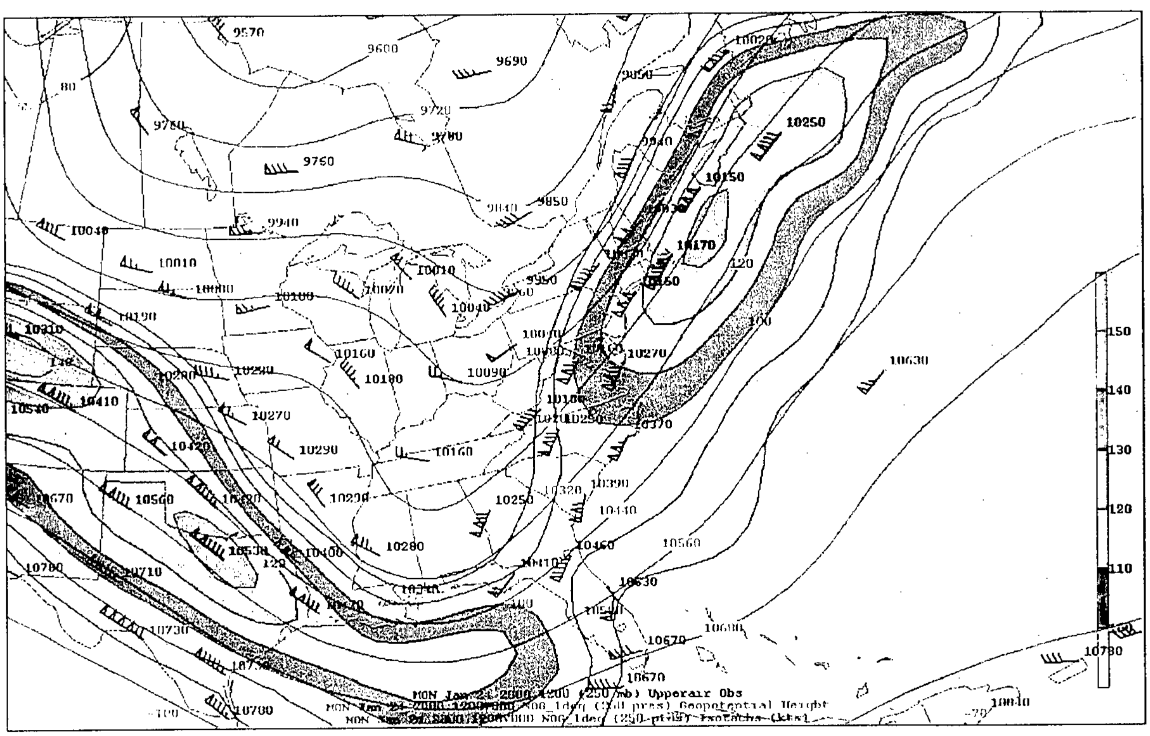


Figure 5.10. NOGAPS 250 mb Heights and Isotachs from the 24/12 Analysis, with Sounding Data.

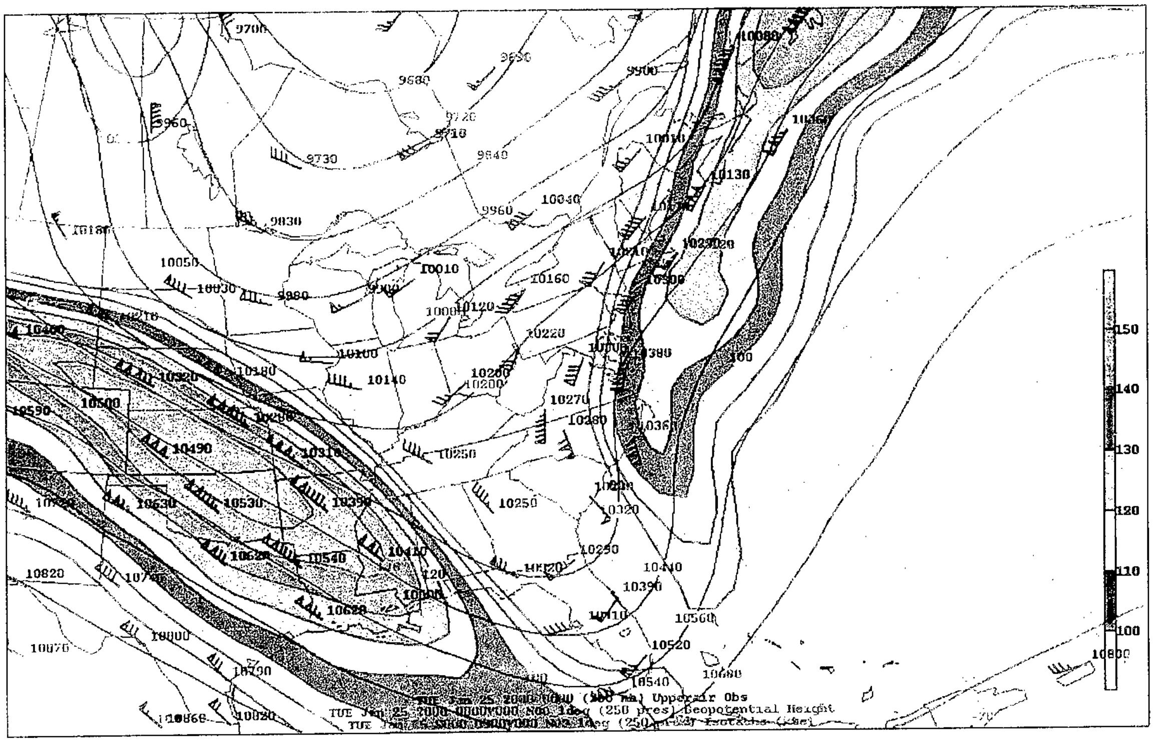


Figure 5.11. NOGAPS 250 mb Heights and Isotachs from the 25/00 Analysis, with Sounding Data.

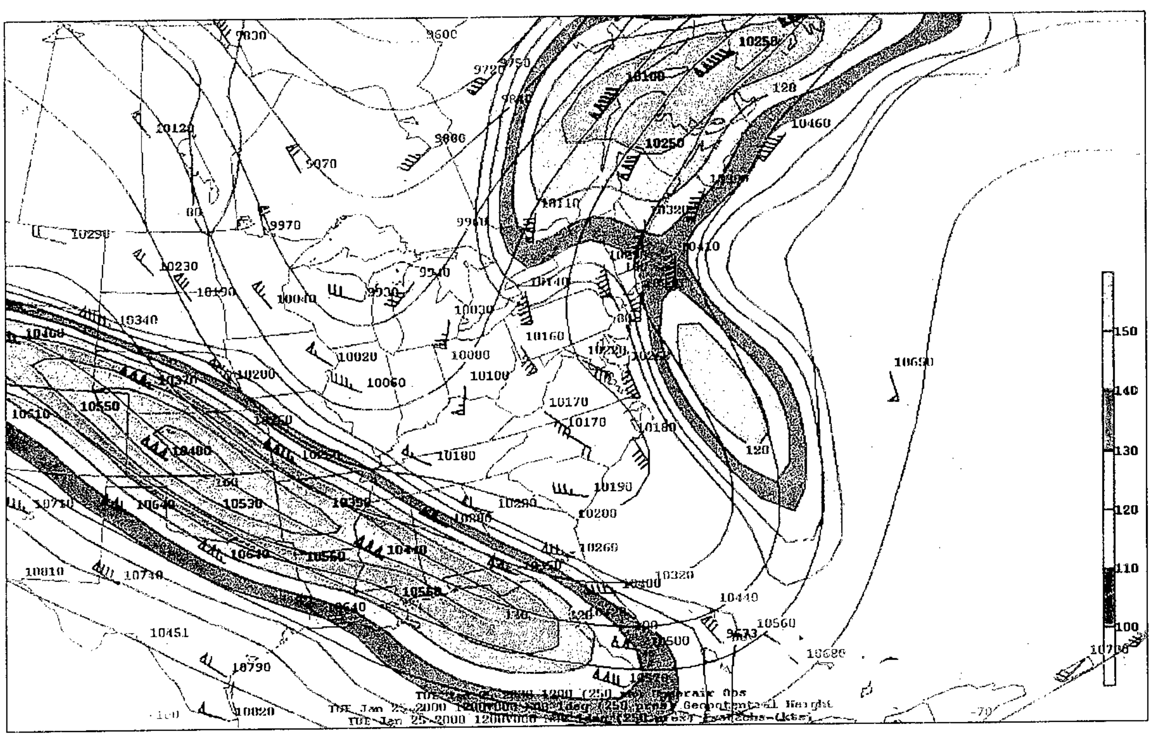


Figure 5.12. NOGAPS 250 mb Heights and Isotachs from the 25/12 Analysis, with Sounding Data.

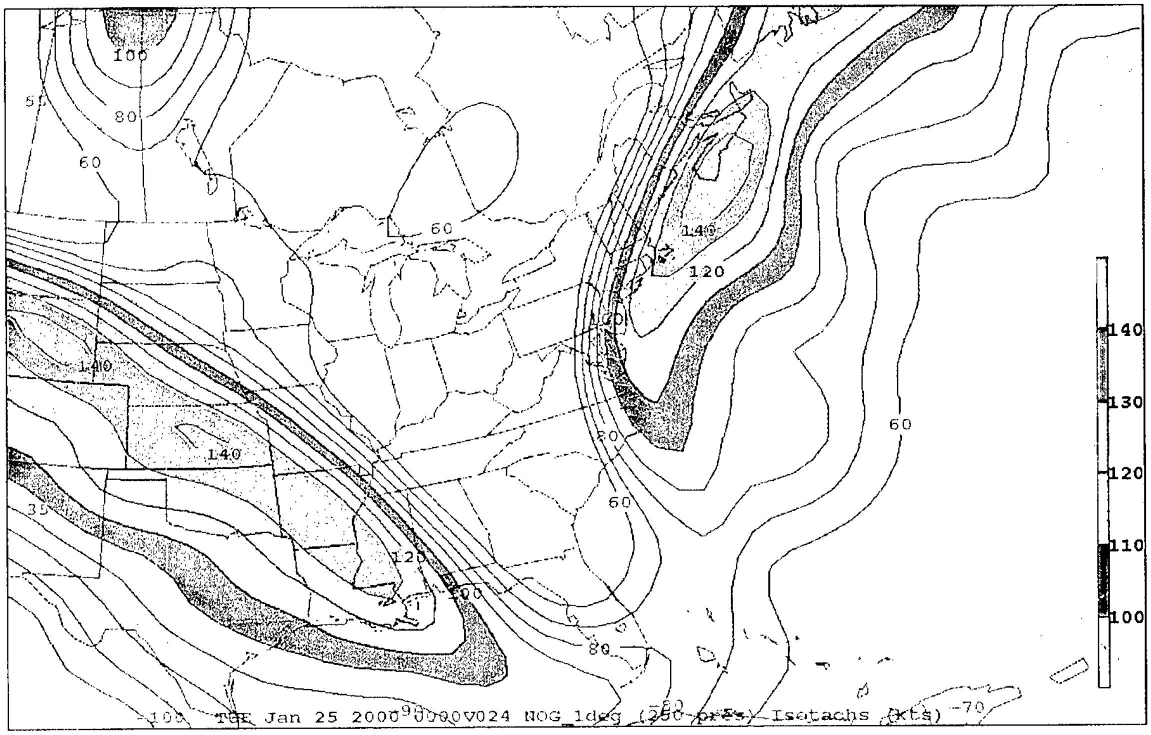


Figure 5.13. NOGAPS 24-Hour 250 mb Isotach Forecast from the 24/00 Run, Valid at 25/00.

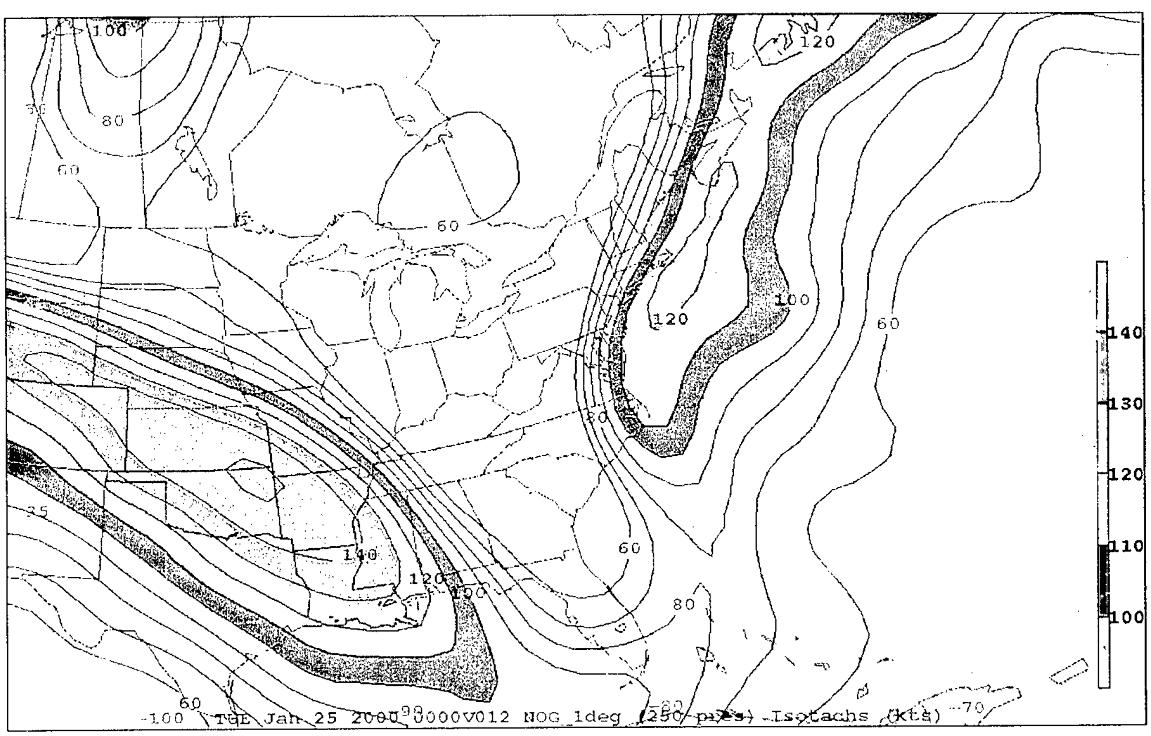


Figure 5.14. NOGAPS 12-Hour 250 mb Isotach Forecast from the 24/12 Run, Valid at 25/00.

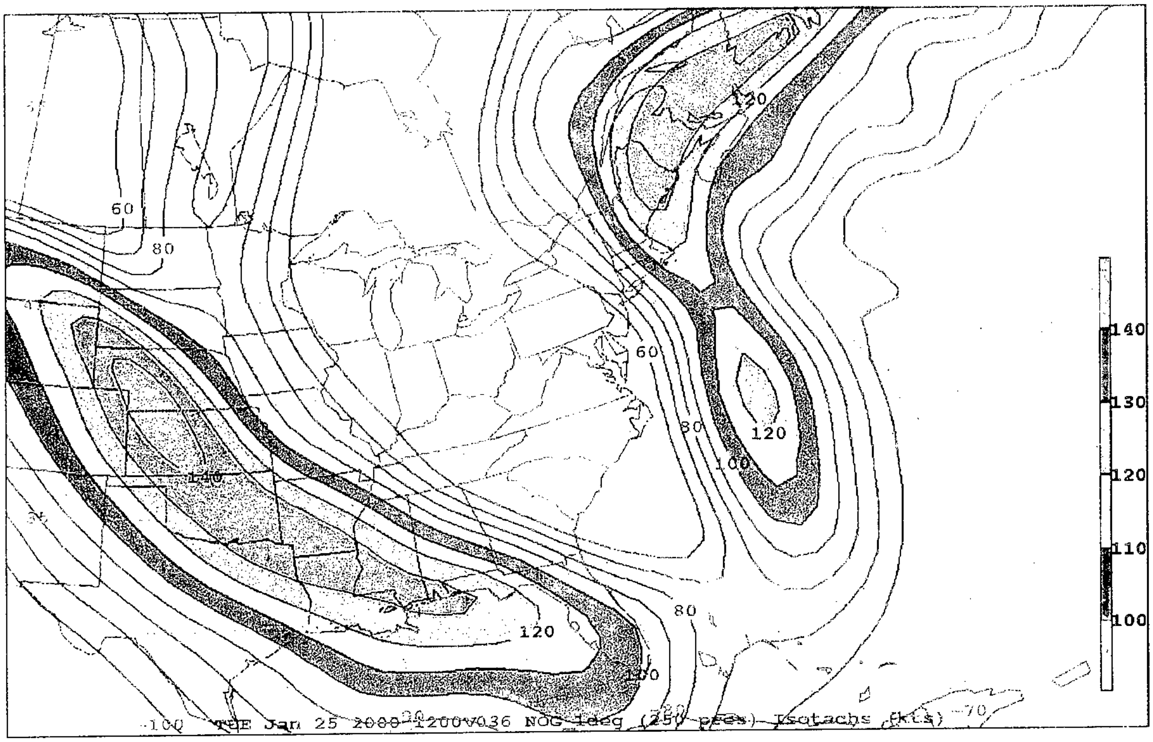


Figure 5.15. NOGAPS 36-Hour 250 mb Isotach Forecast from the 24/00 Run, Valid at 25/12.

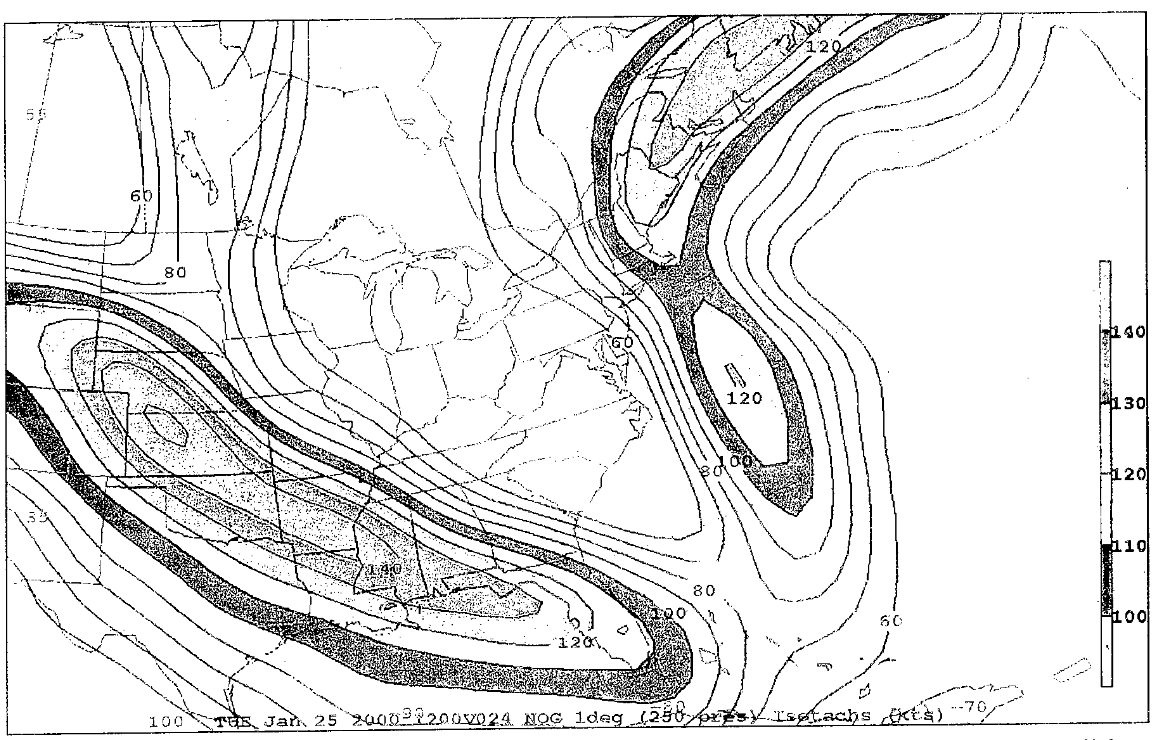


Figure 5.16. NOGAPS 24-Hour 250 mb Isotach Forecast from the 24/12 Run, Valid at 25/12.

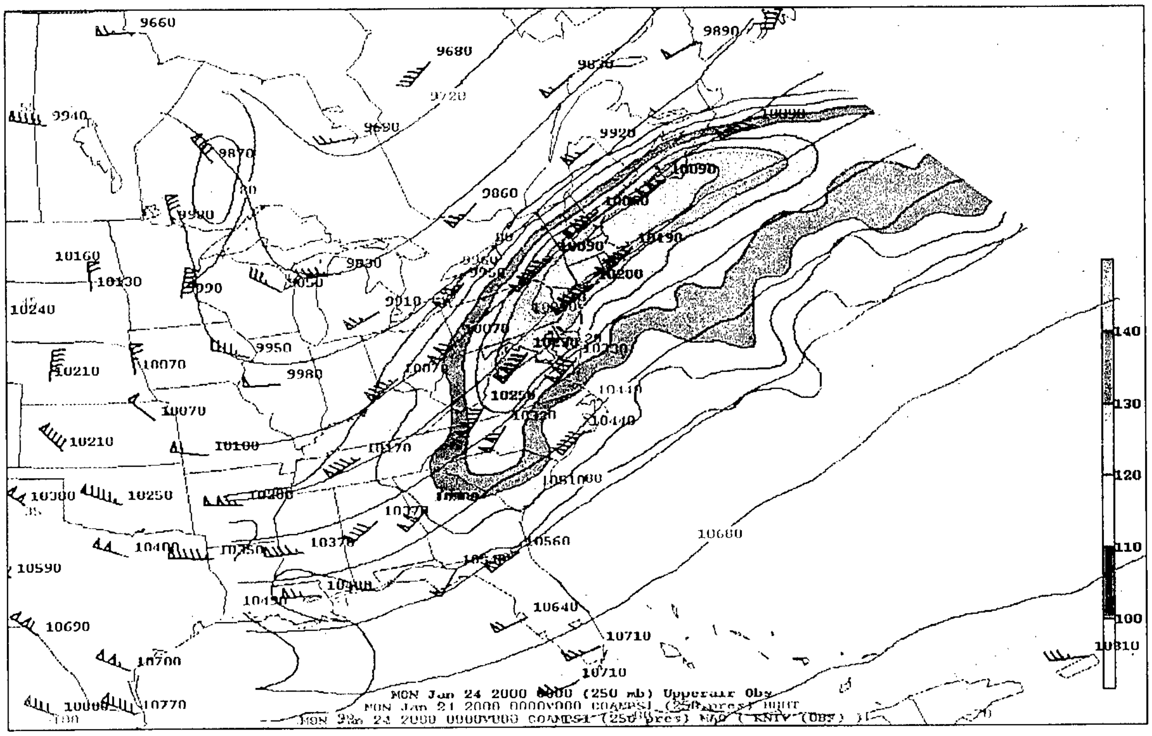


Figure 5.17. COAMPS 250 mb Heights and Isotachs from the 24/00 Analysis, with Sounding Data.

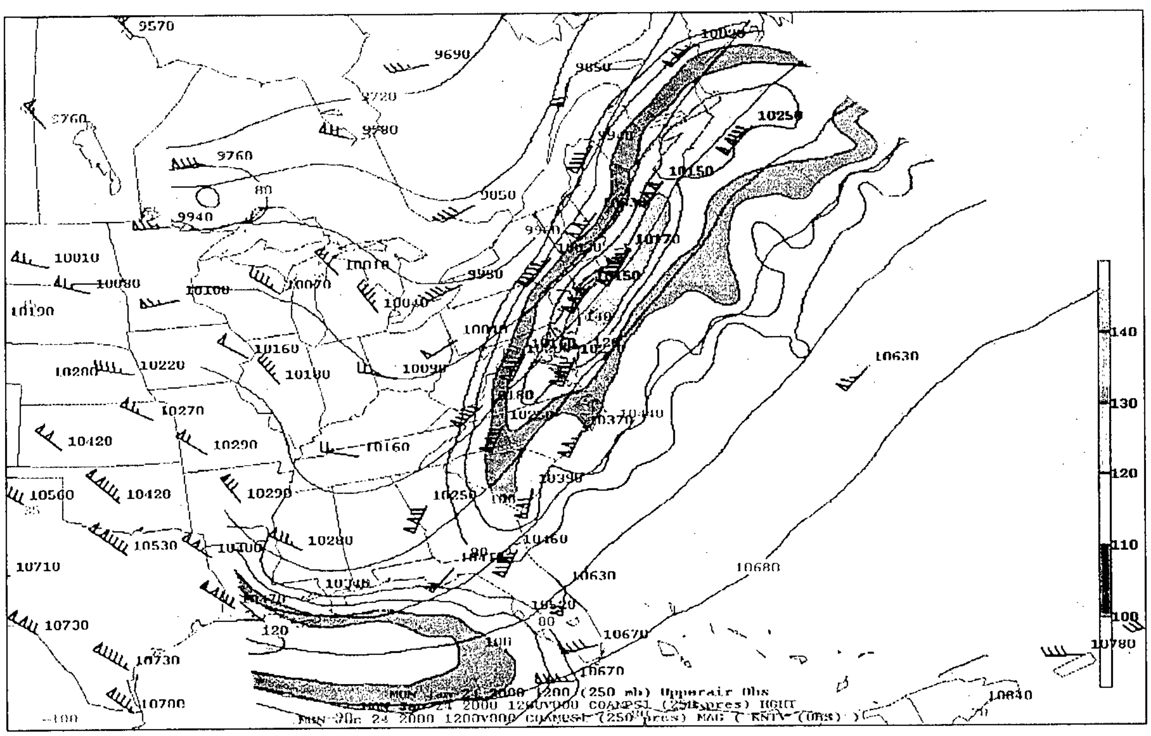


Figure 5.18. COAMPS 250 mb Heights and Isotachs from the 24/12 Analysis, with Sounding Data.

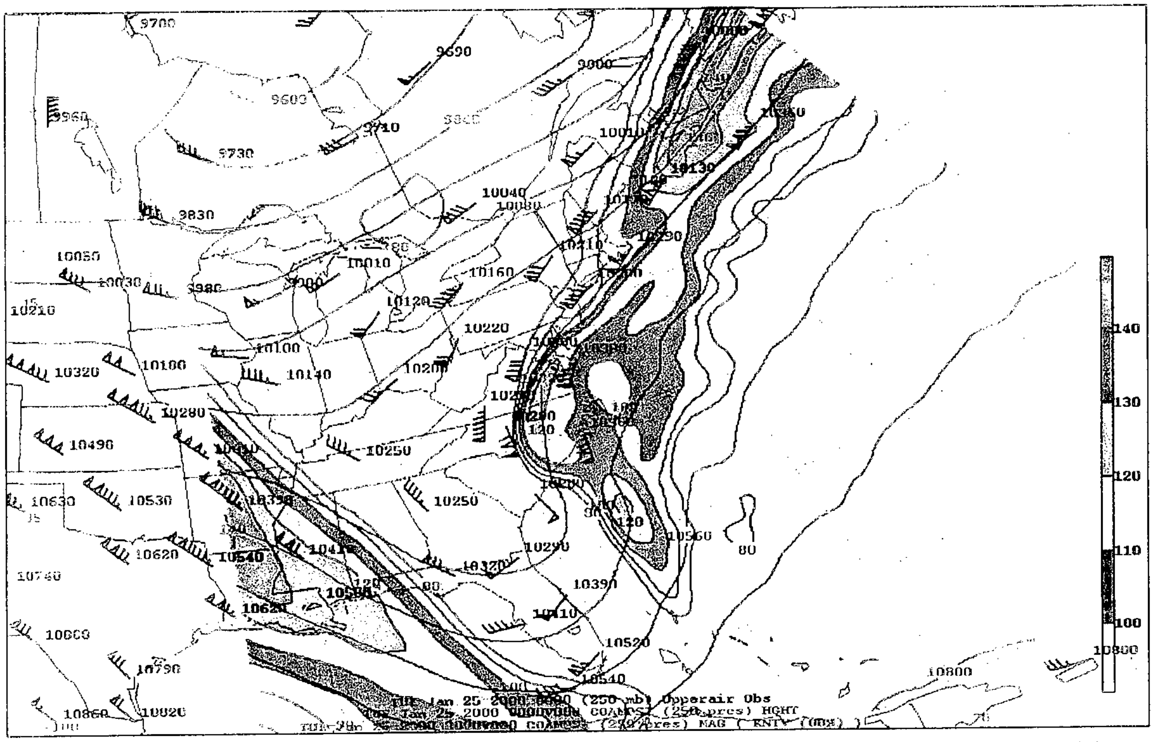


Figure 5.19. COAMPS 250 mb Heights and Isotachs from the 25/00 Analysis, with Sounding Data.

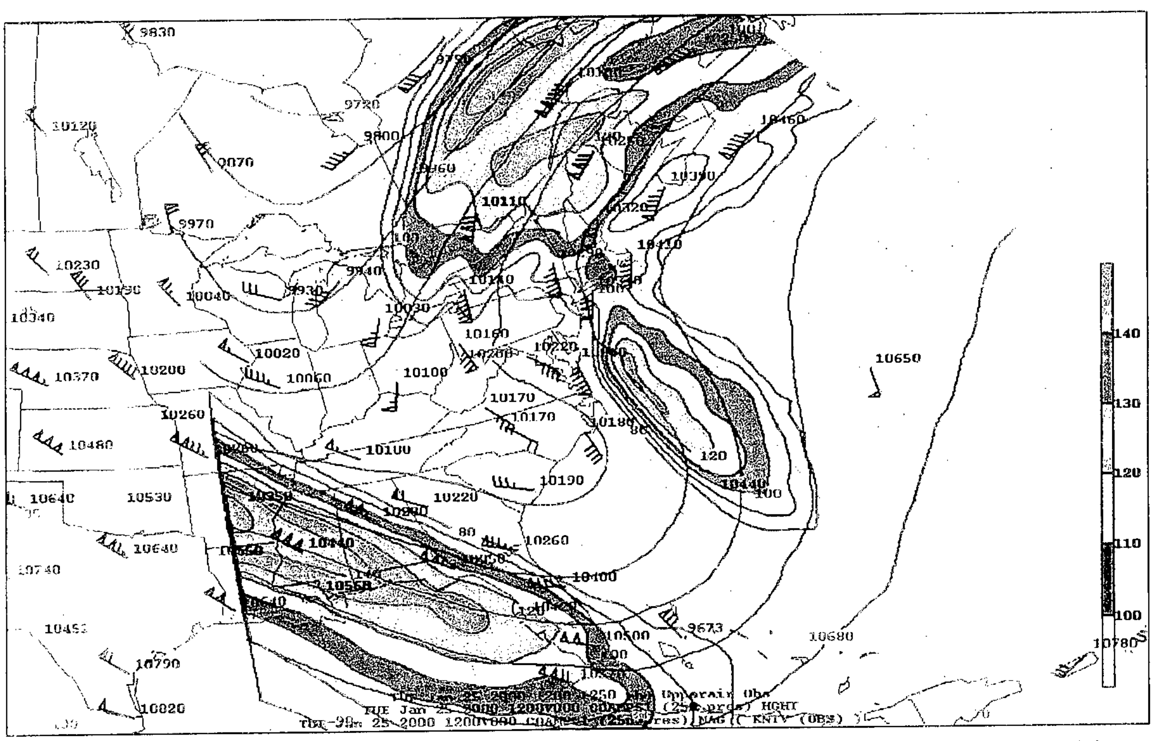


Figure 5.20. COAMPS 250 mb Heights and Isotachs from the 25/12 Analysis, with Sounding Data.

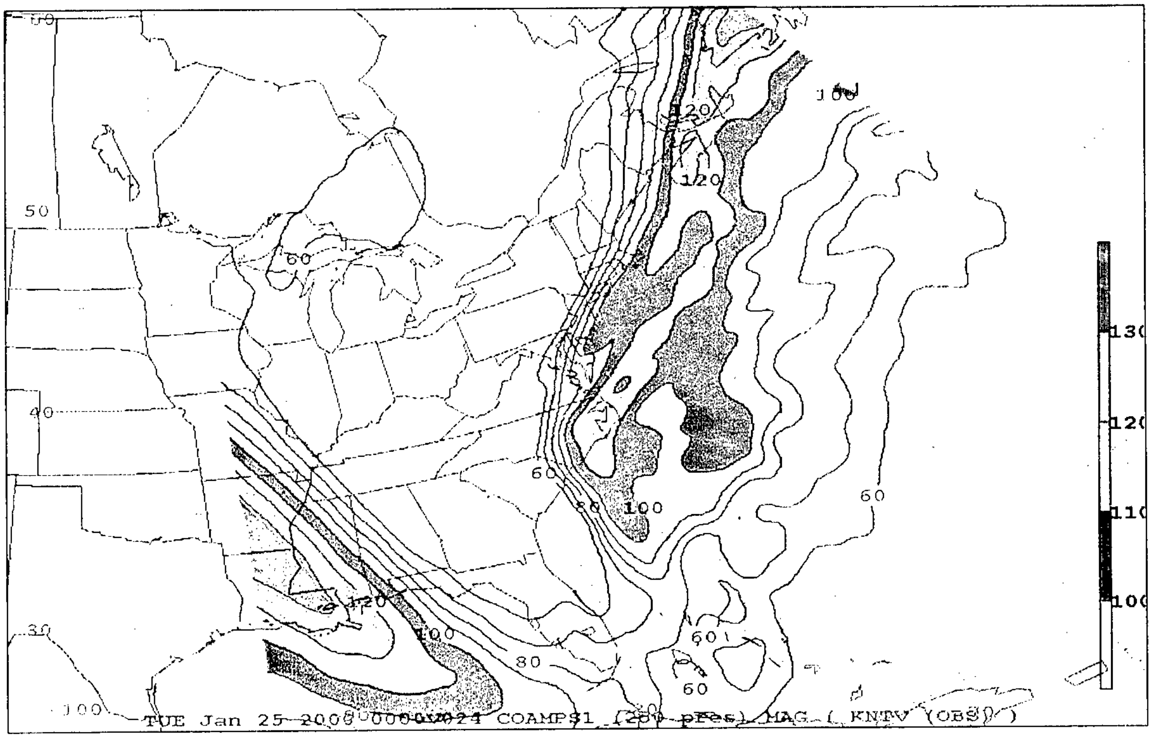


Figure 5.21. COAMPS 24-Hour 250 mb Isotach Forecast from the 24/00 Run, Valid at 25/00.

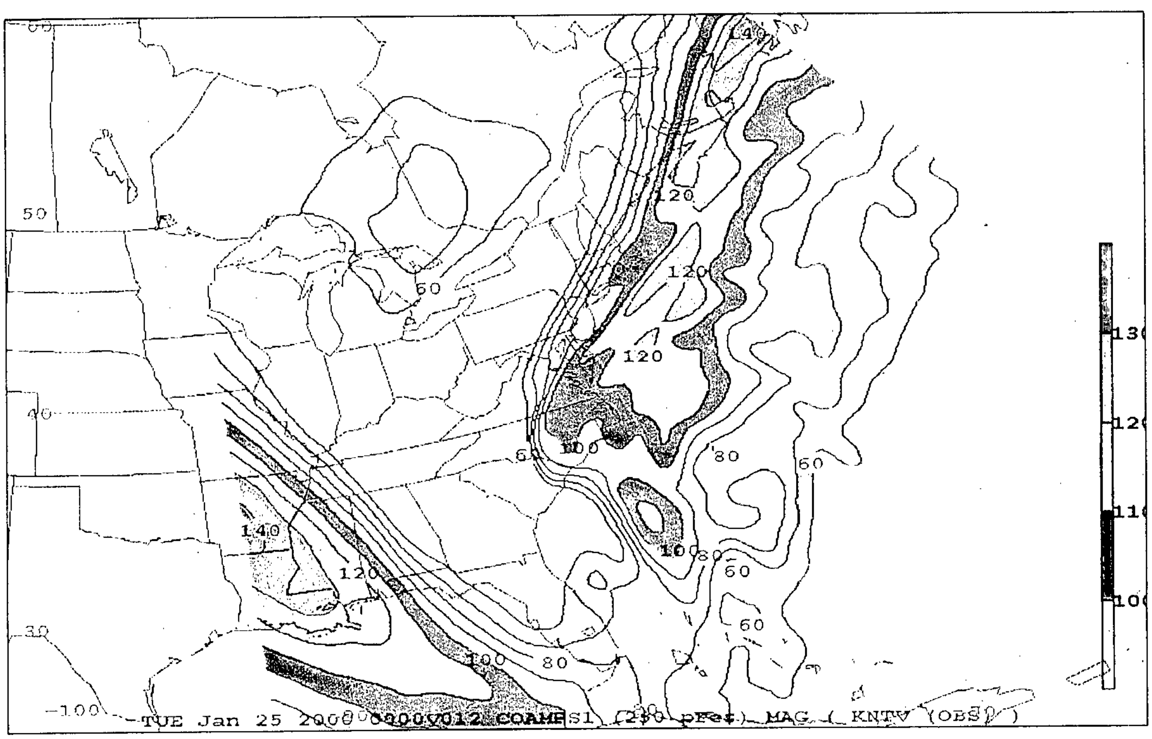


Figure 5.22. COAMPS 12-Hour 250 mb Isotach Forecast from the 24/12 Run, Valid at 25/00.

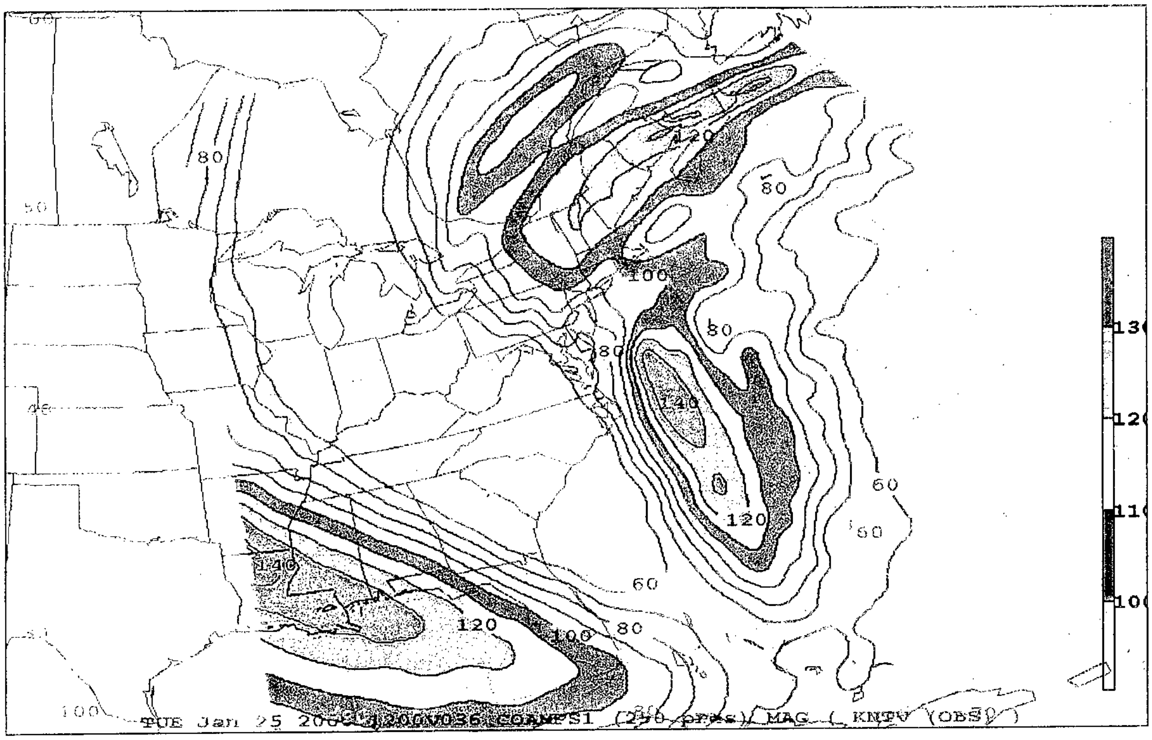


Figure 5.23. COAMPS 36-Hour 250 mb Isotach Forecast from the 24/00 Run, Valid at 25/12.

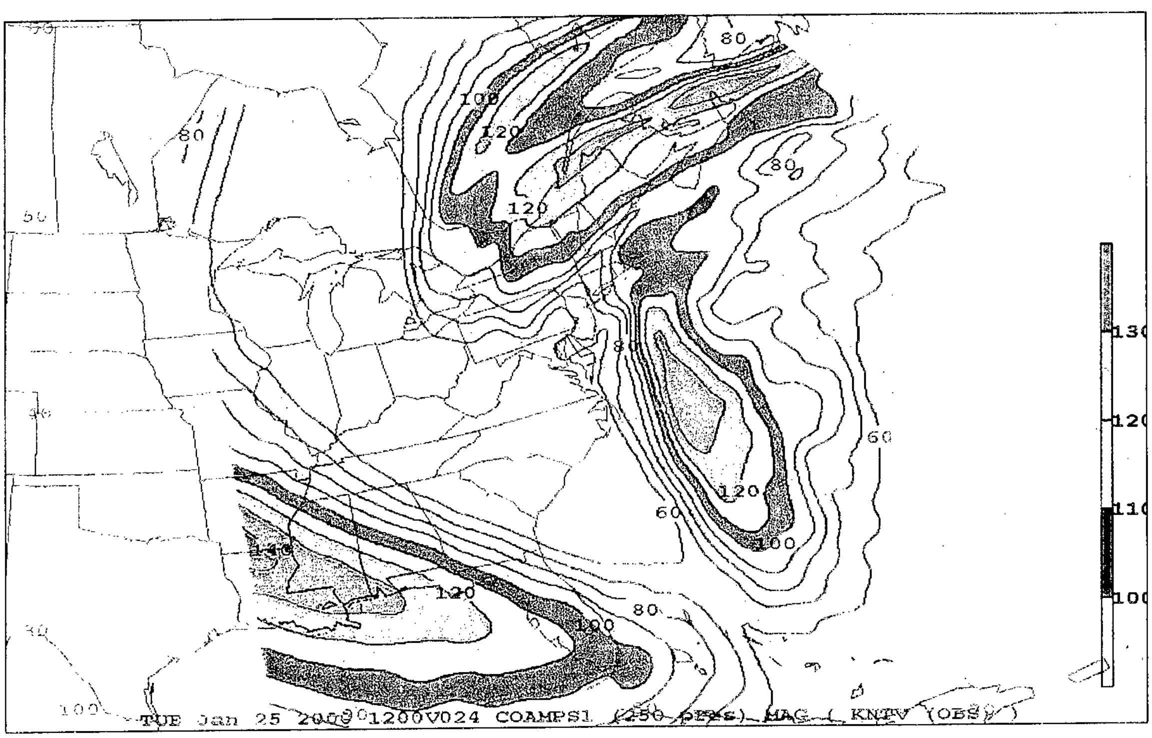


Figure 5.24. COAMPS 24-Hour 250 mb Isotach Forecast from the 24/12 Run, Valid at 25/12.

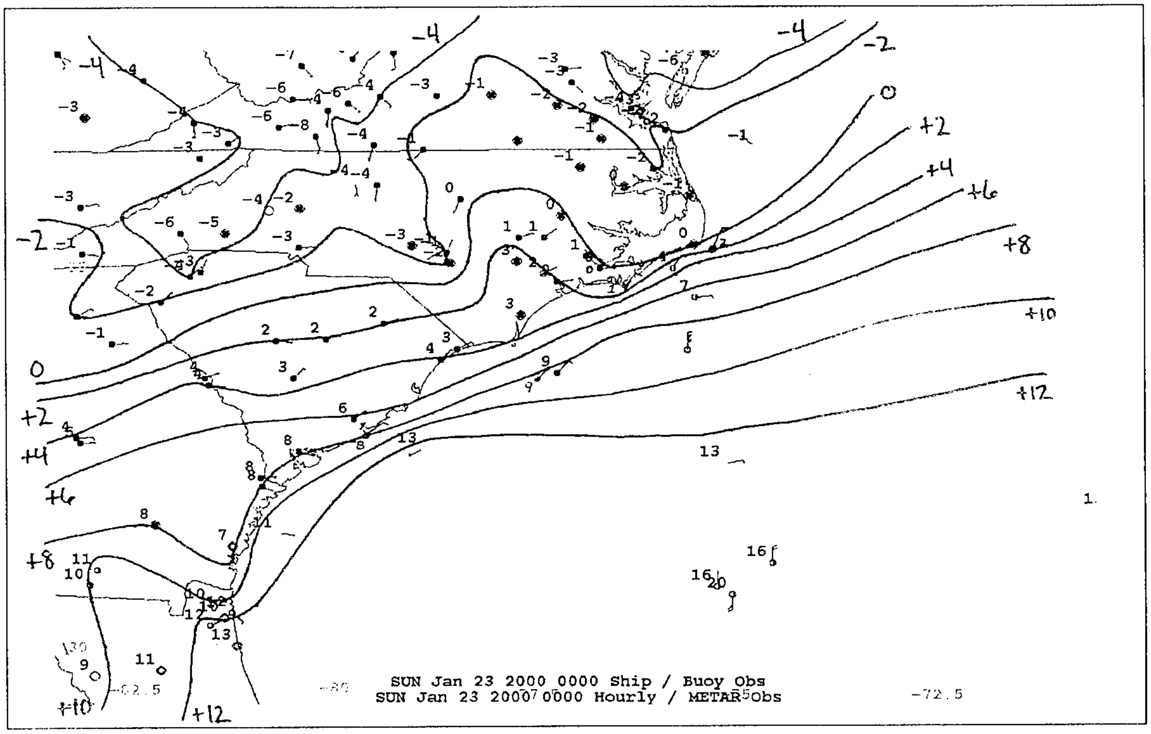


Figure 5.25. Manual Surface Temperature Analysis For 23/00.

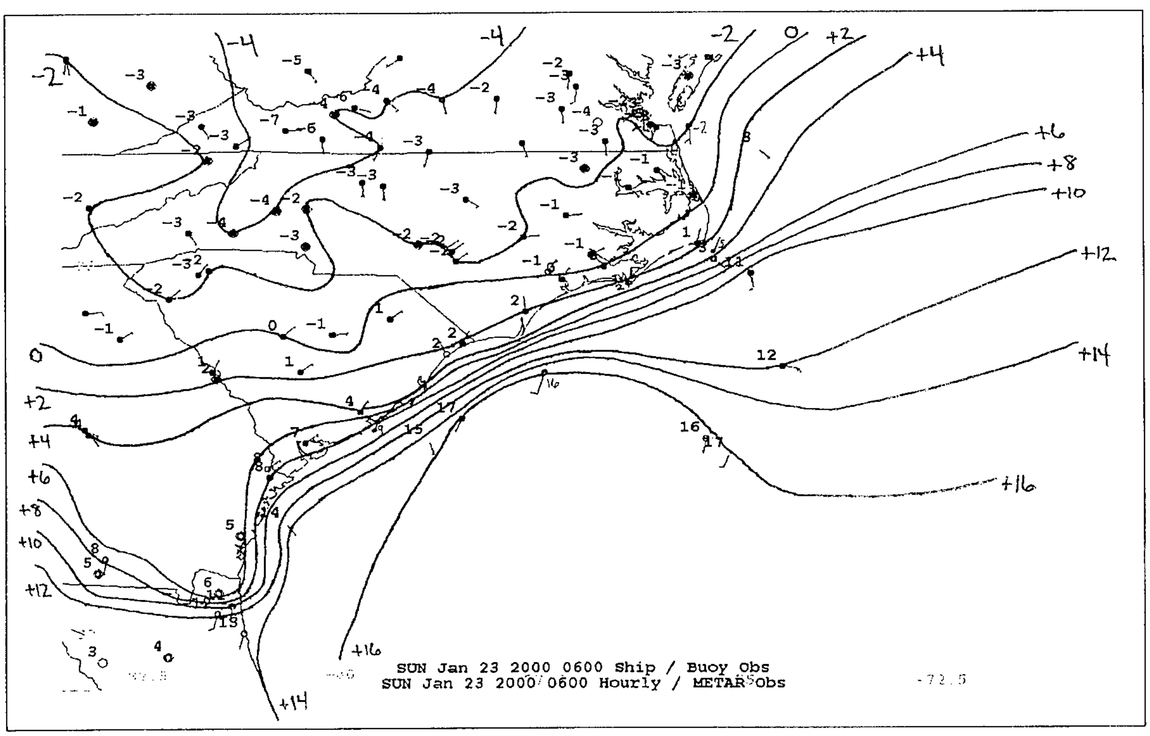


Figure 5.26. Manual Surface Temperature Analysis For 23/06.

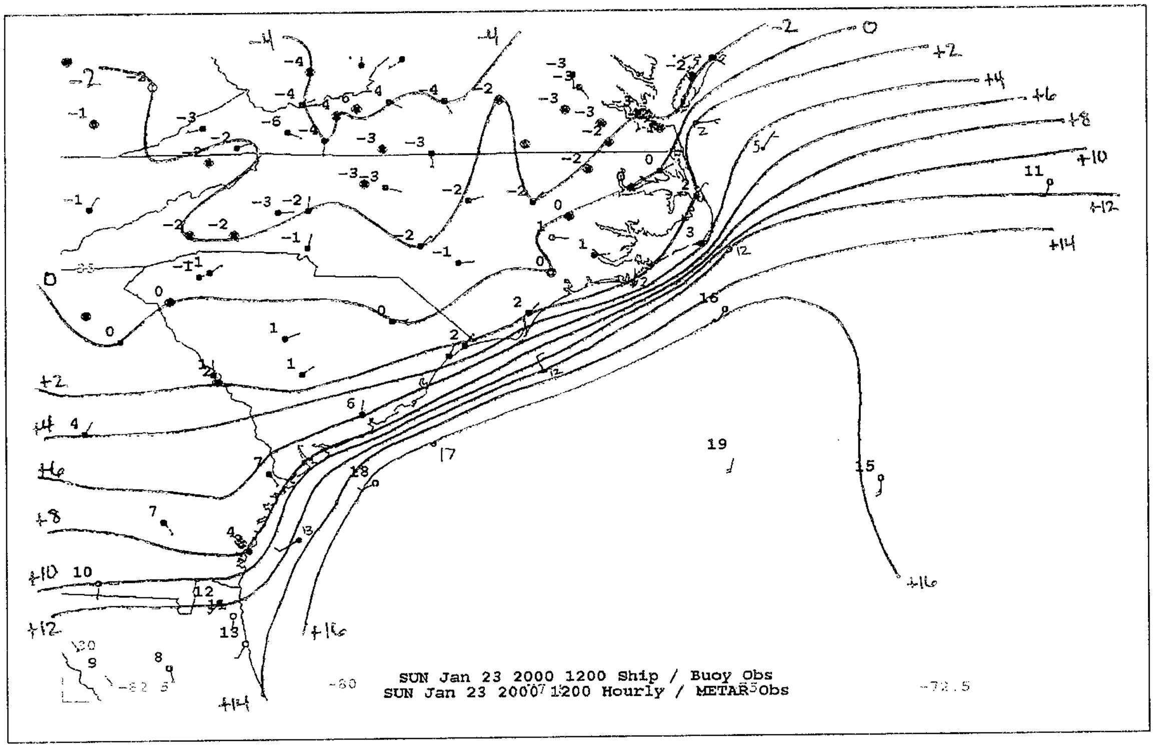


Figure 5.27. Manual Surface Temperature Analysis For 23/12.

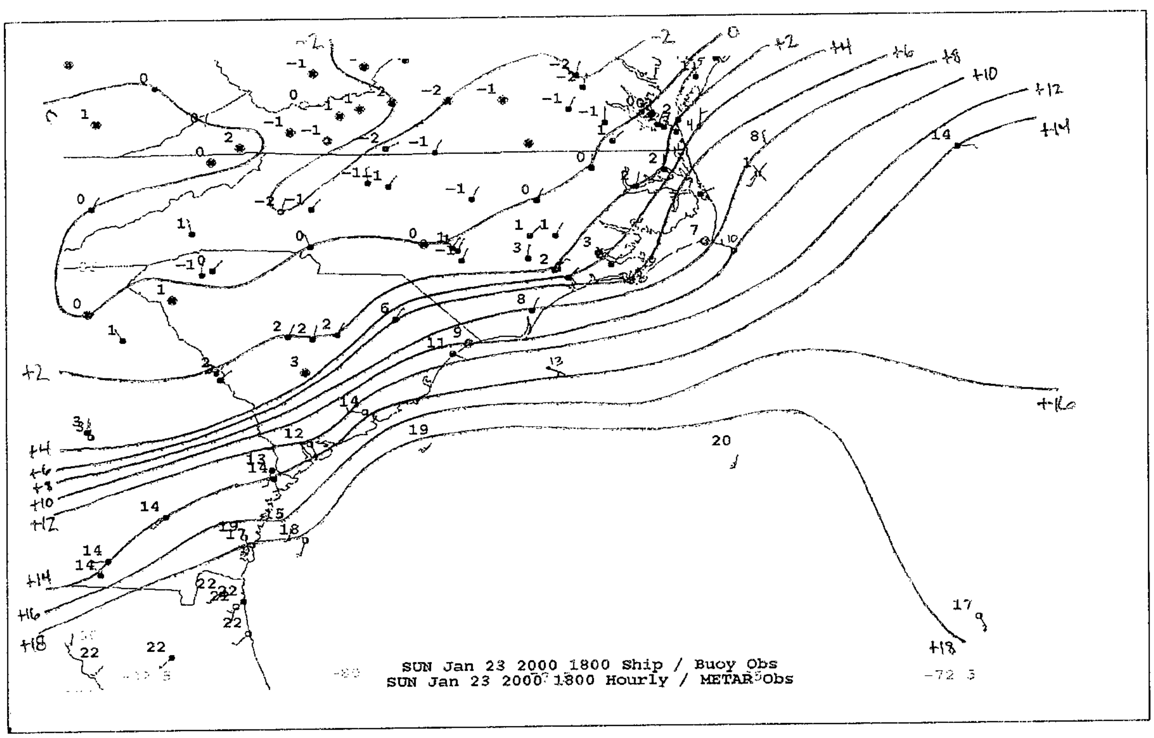


Figure 5.28. Manual Surface Temperature Analysis For 23/18.

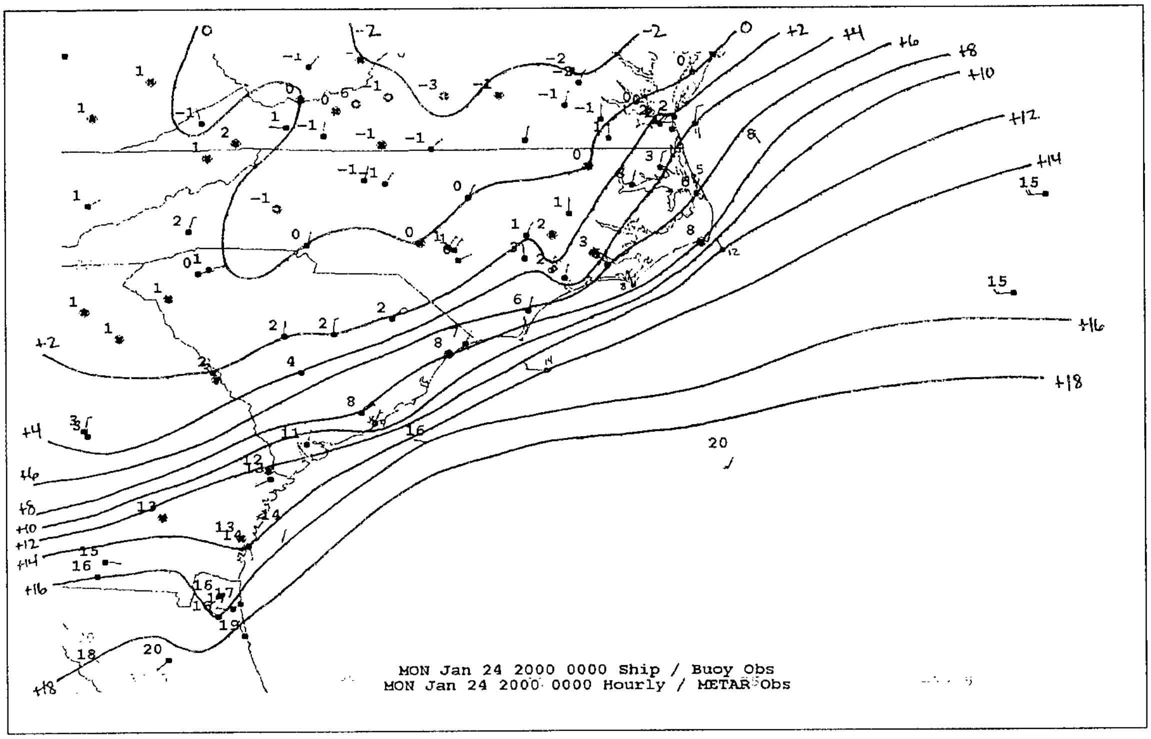


Figure 5.29. Manual Surface Temperature Analysis For 24/00.

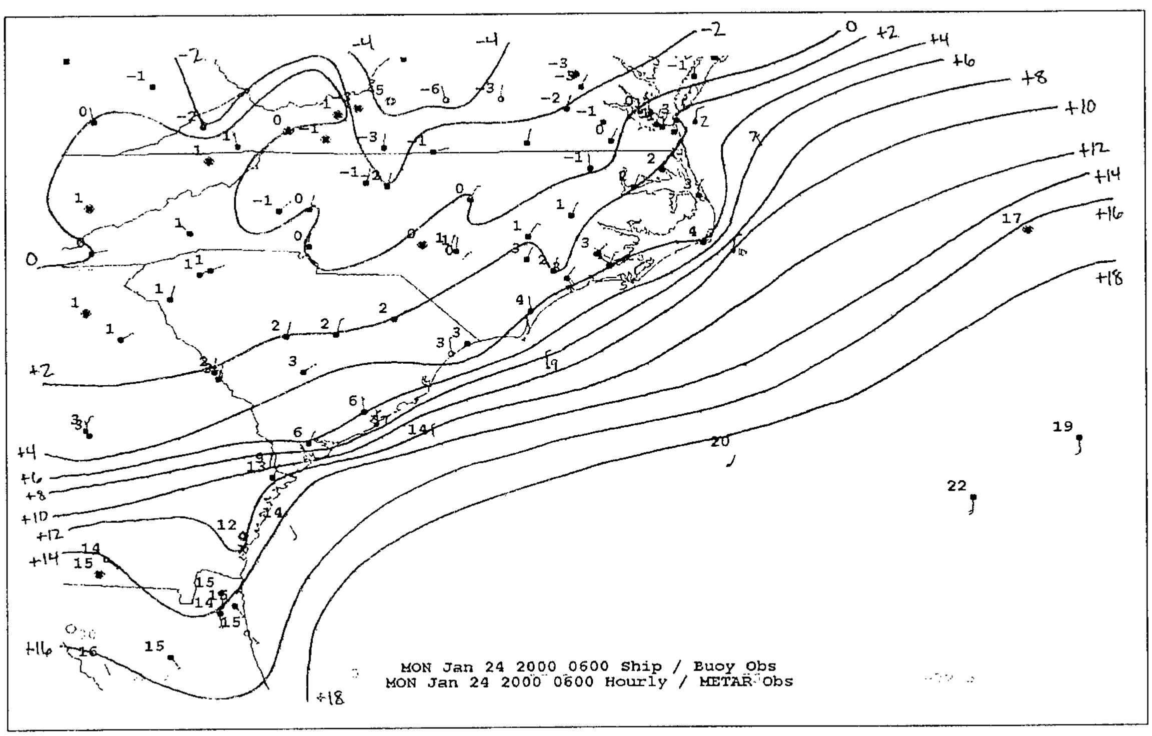


Figure 5.30. Manual Surface Temperature Analysis For 24/06.

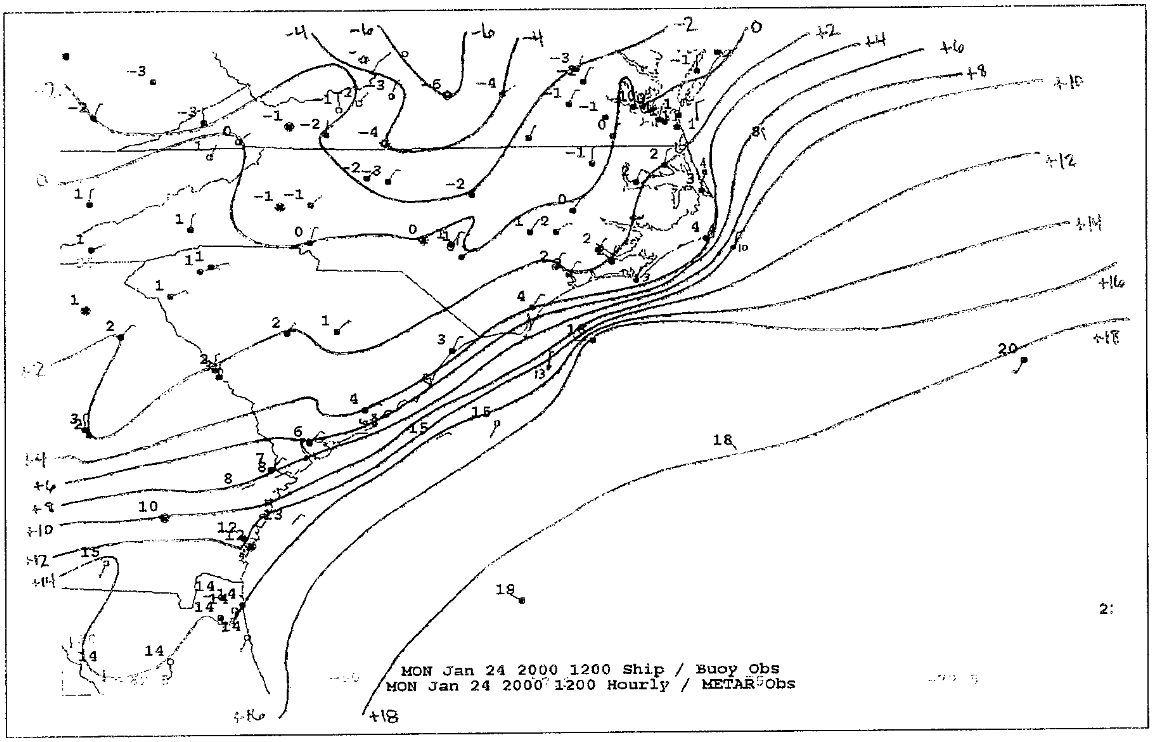


Figure 5.31. Manual Surface Temperature Analysis For 24/12.

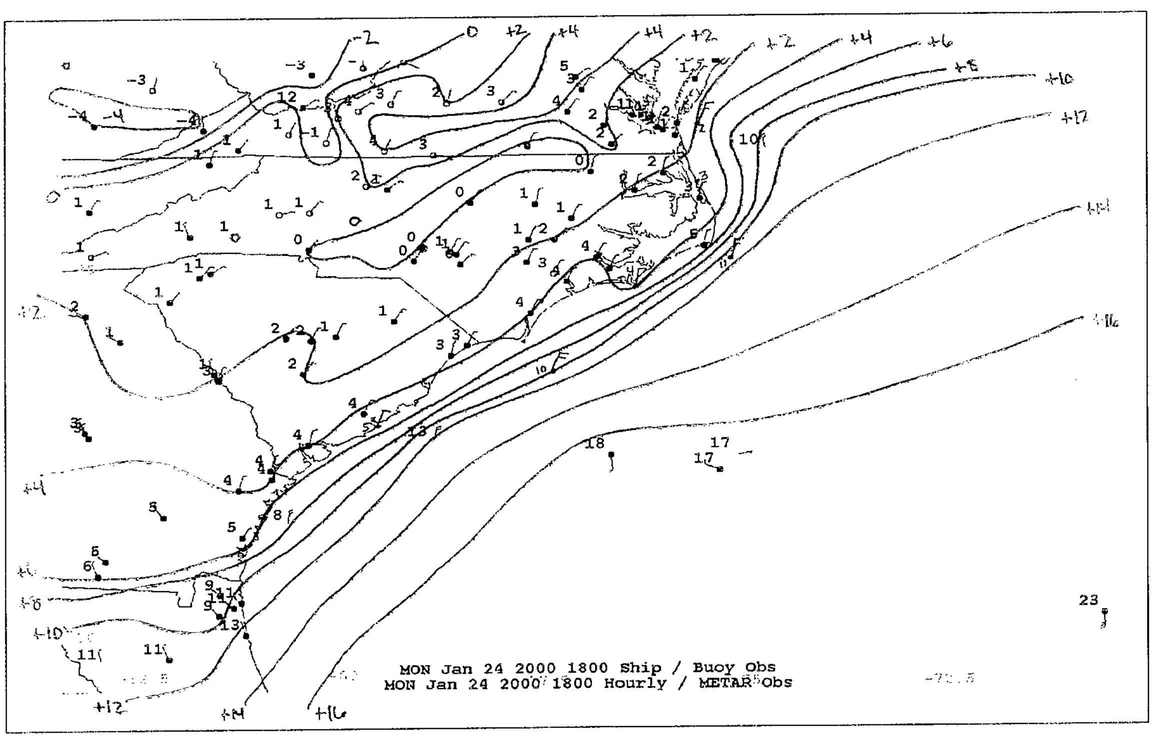


Figure 5.32. Manual Surface Temperature Analysis For 24/18.

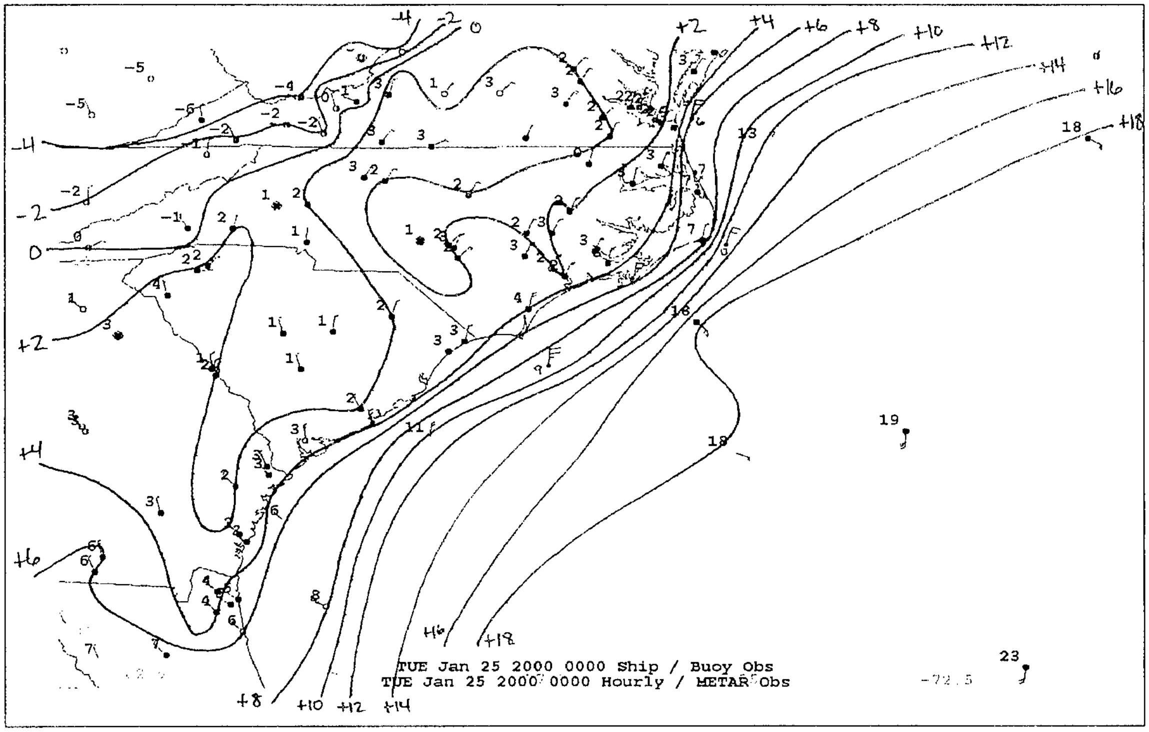


Figure 5.33. Manual Surface Temperature Analysis For 25/00.

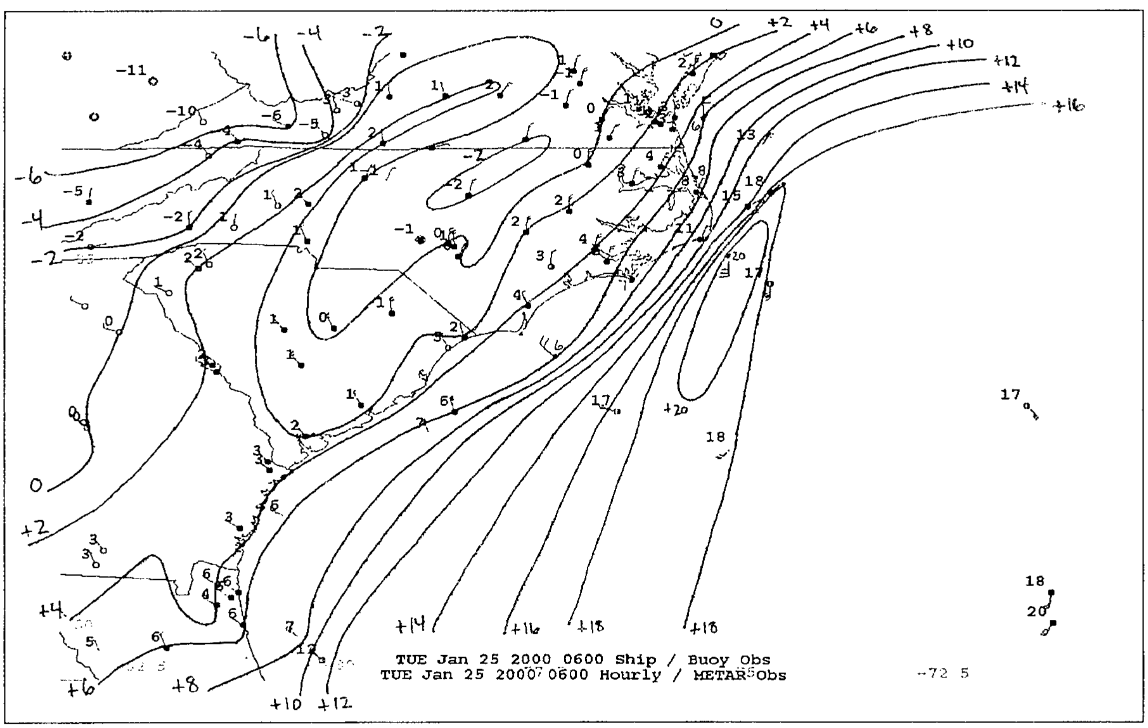


Figure 5.34. Manual Surface Temperature Analysis For 25/06.

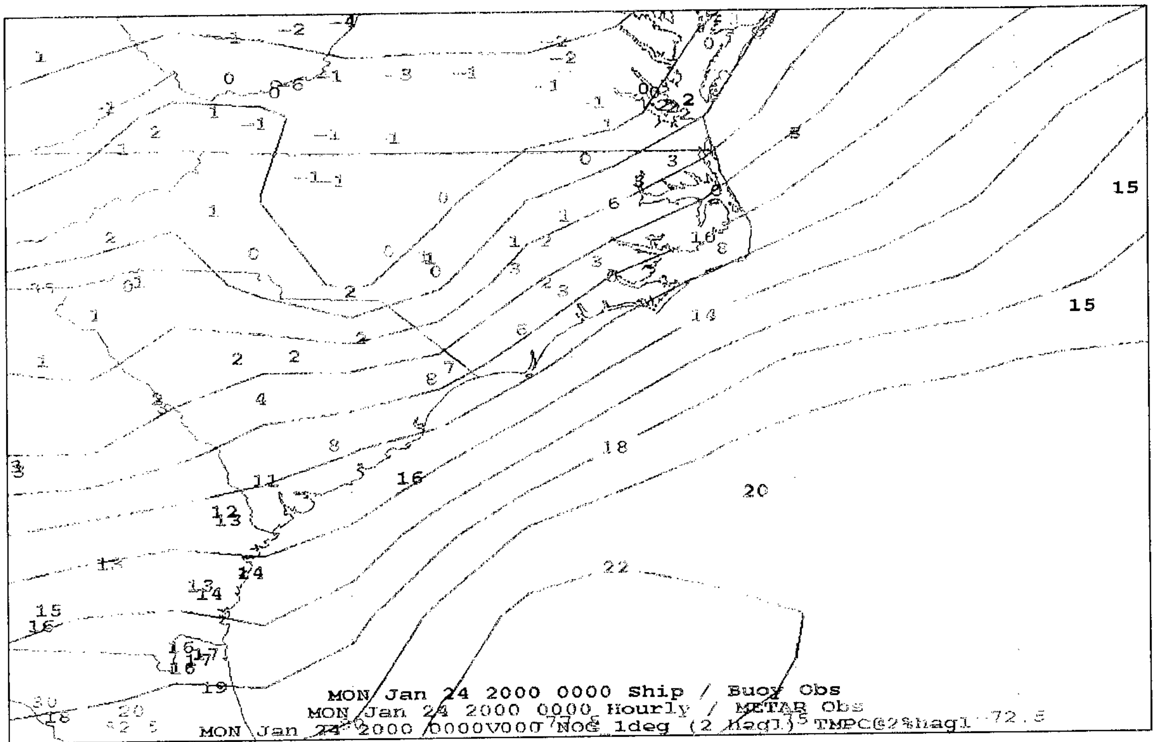


Figure 5.35. NOGAPS 24/00 Surface Temperature Analysis with METAR, Ship, and Buoy Obs.

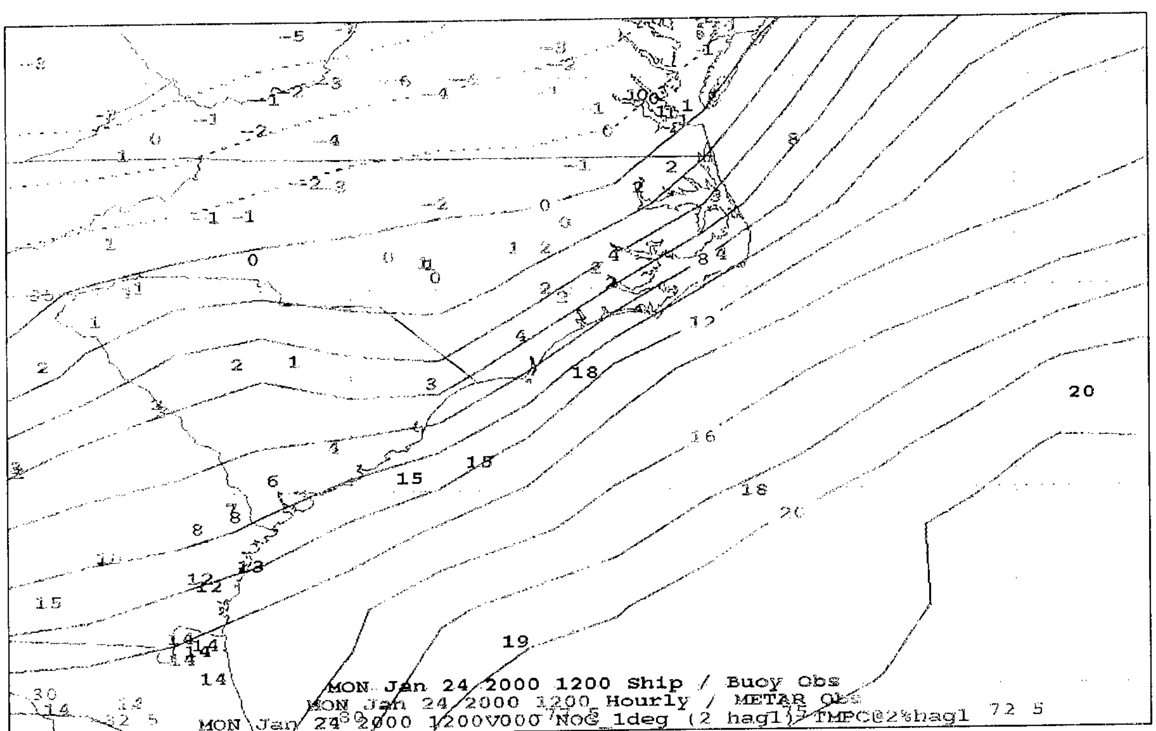


Figure 5.36. NOGAPS 24/12 Surface Temperature Analysis with METAR, Ship, and Buoy Obs.

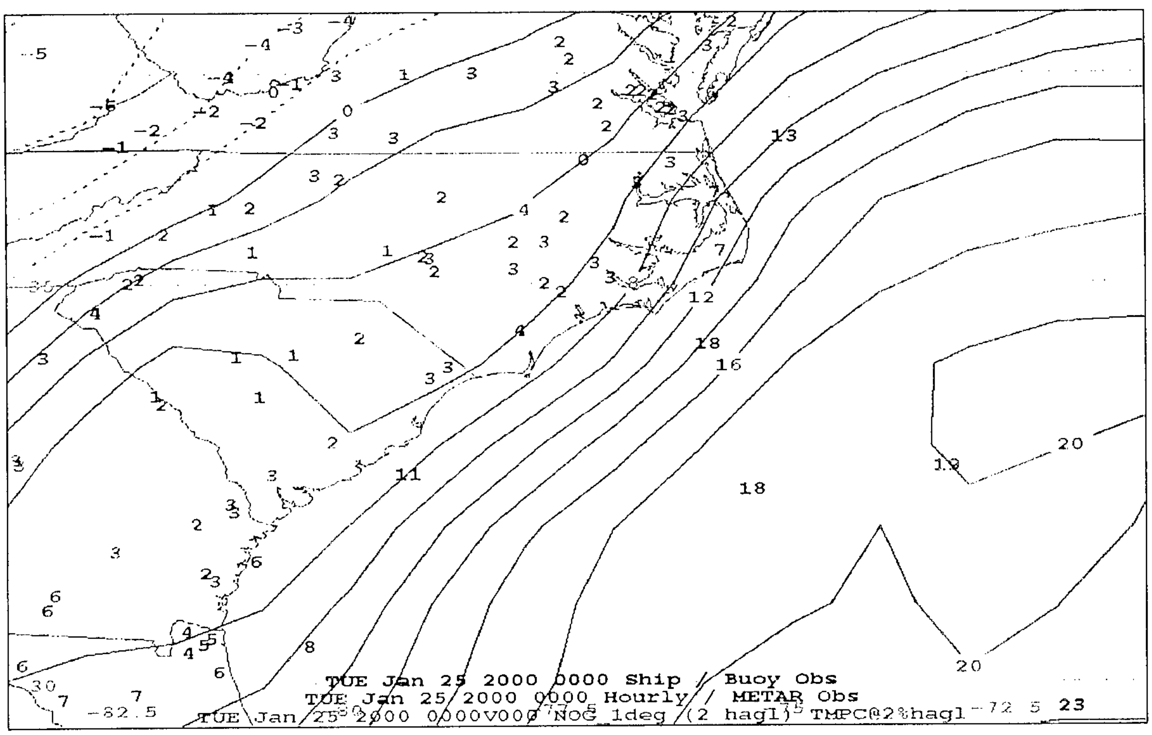


Figure 5.37. NOGAPS 25/00 Surface Temperature Analysis with METAR, Ship, and Buoy Obs.

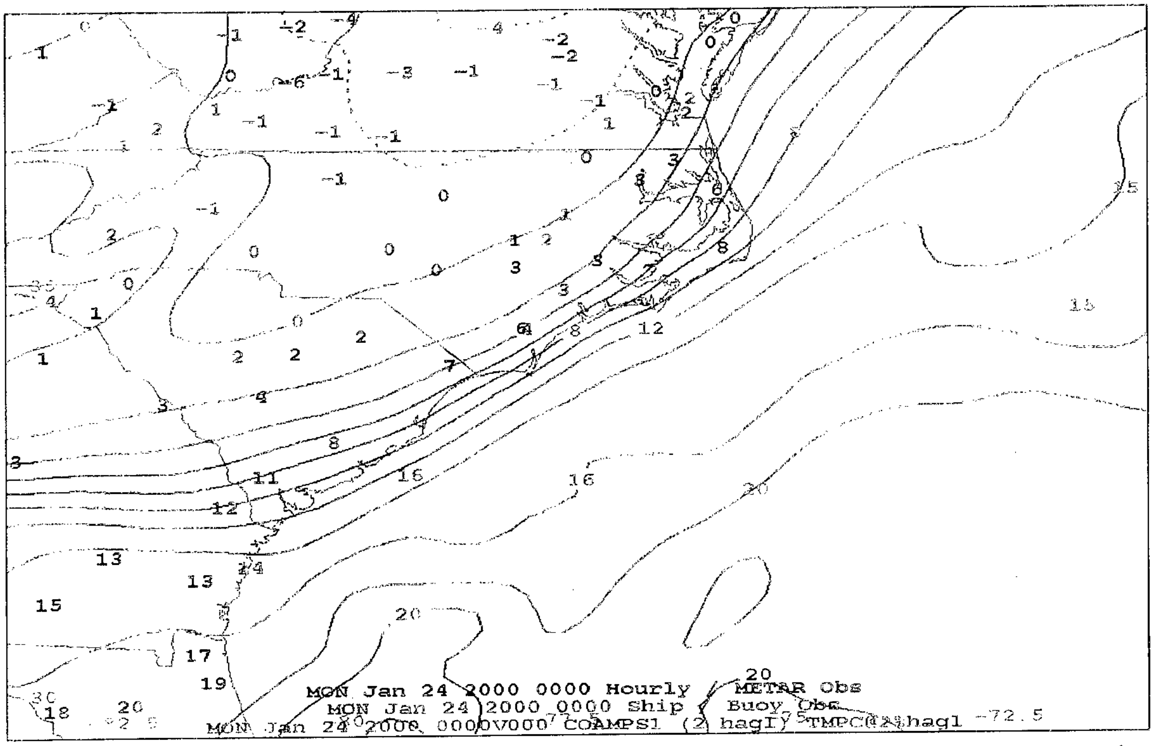


Figure 5.38. COAMPS 24/00 Surface Temperature Analysis with METAR, Ship, and Buoy Obs.

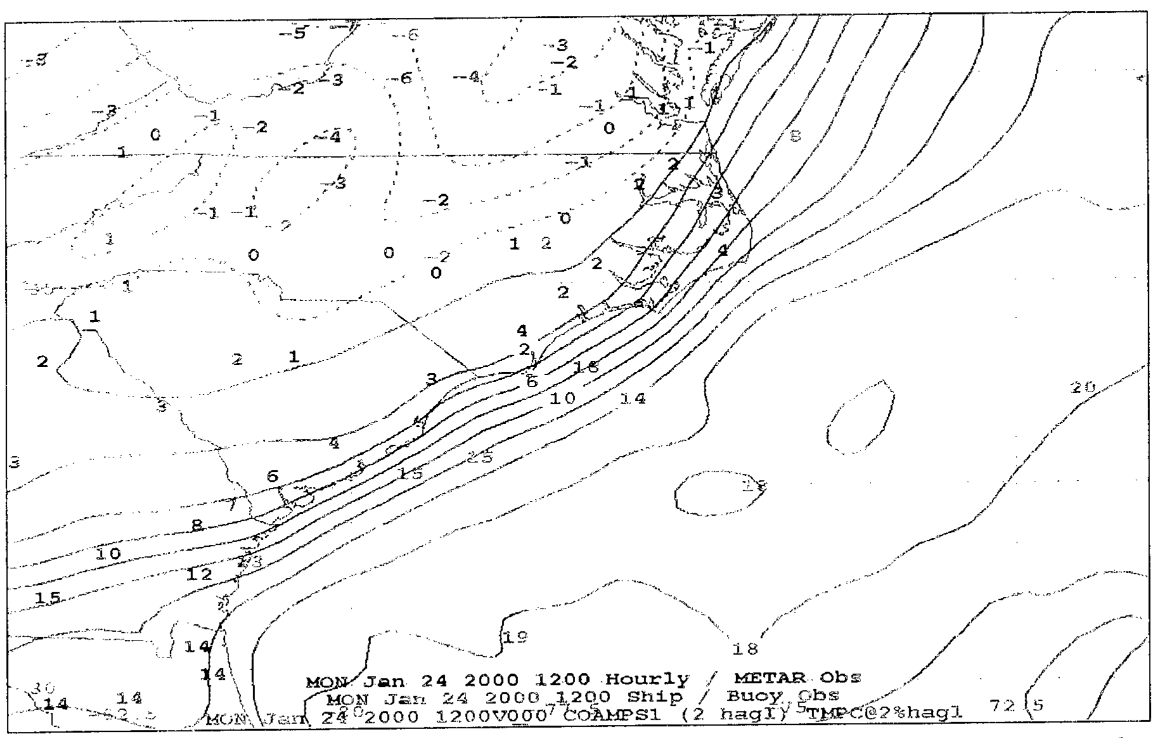


Figure 5.39. COAMPS 24/12 Surface Temperature Analysis with METAR, Ship, and Buoy Obs.

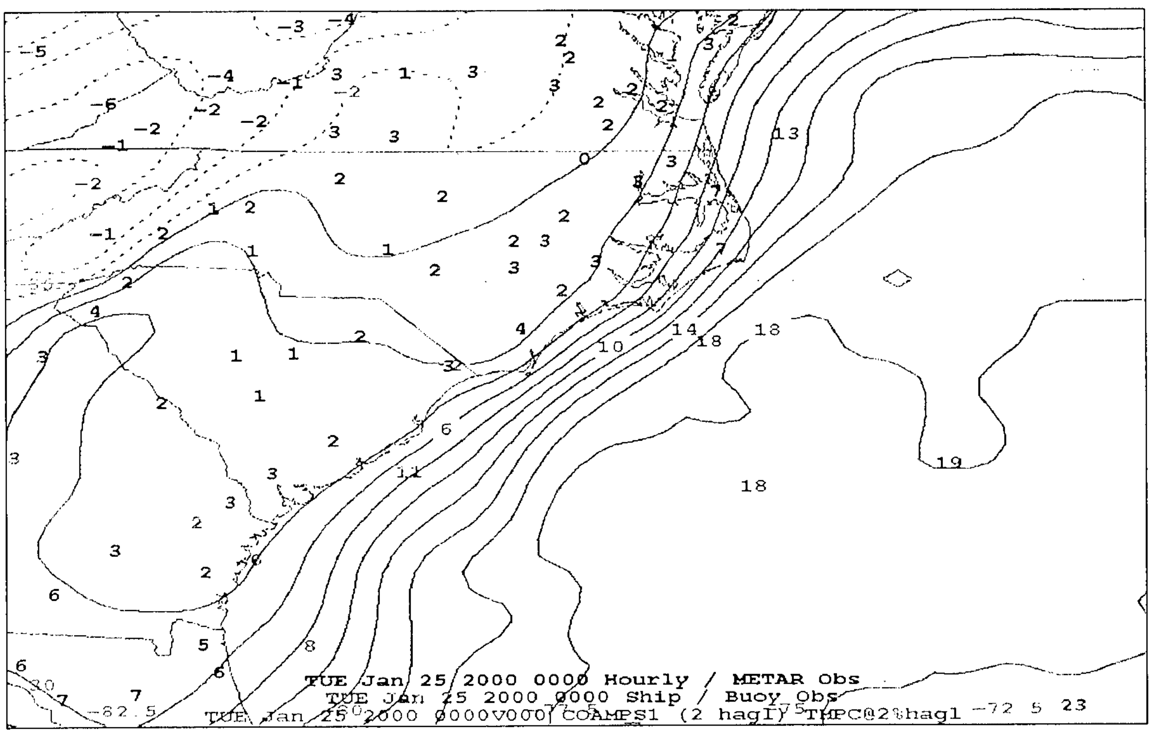


Figure 5.40. COAMPS 25/00 Surface Temperature Analysis with METAR, Ship, and Buoy Obs.

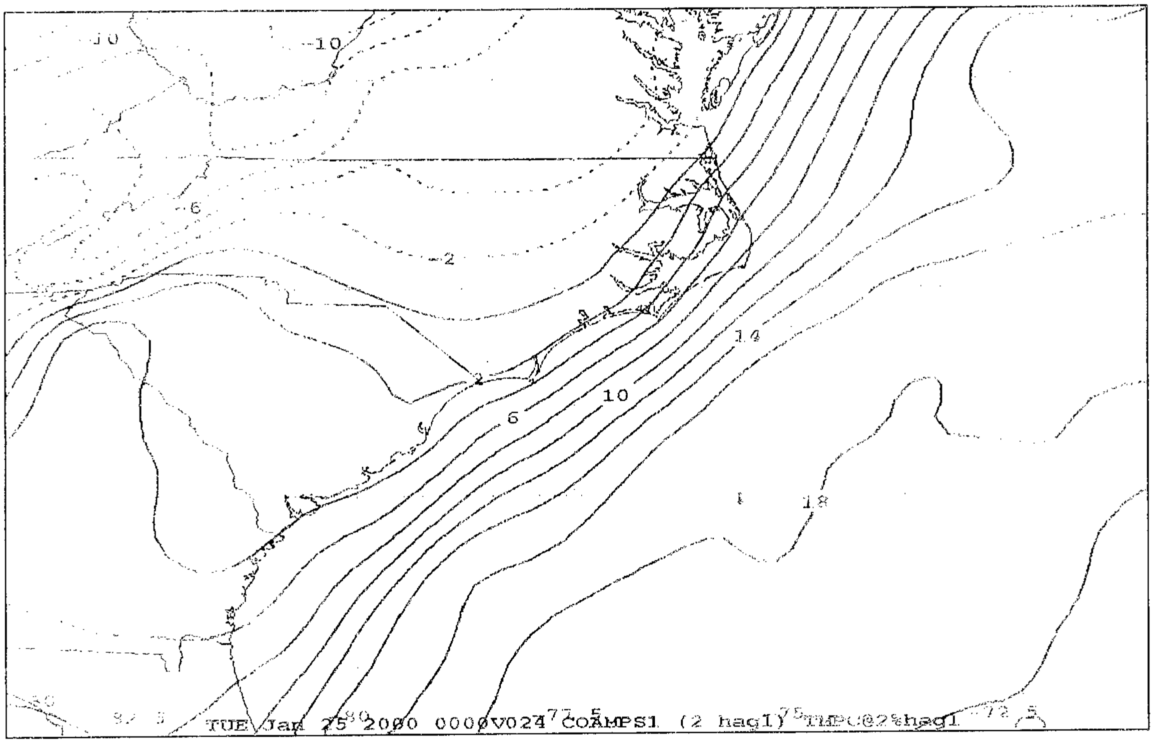


Figure 5.41. COAMPS 24-Hour Surface Temperature Forecast from the 24/00 Run, Valid at 25/00.

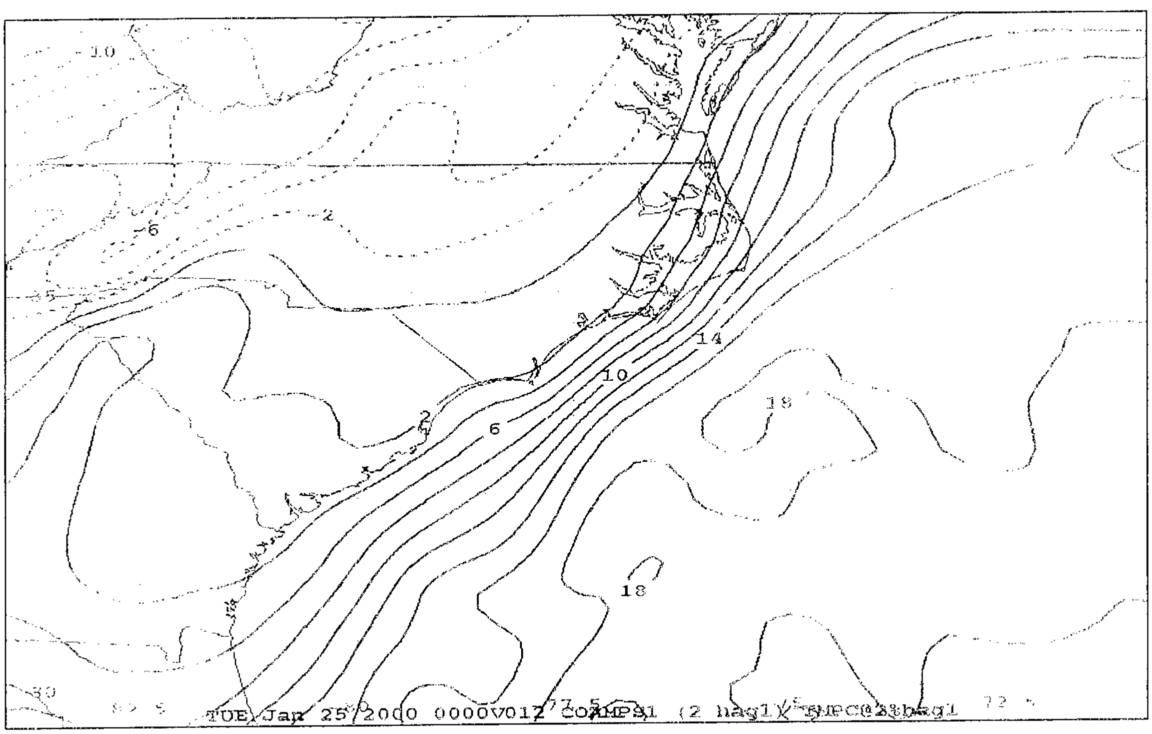


Figure 5.42. COAMPS 12-Hour Surface Temperature Forecast from the 24/12 Run, Valid at 25/00.

VI. NAVDAS

This chapter will discuss some preliminary findings for NOGAPS runs initialized with NAVDAS. This variational data assimilation scheme is scheduled to be implemented into the operational NOGAPS by the end of 2001. It must be noted that the products presented in this chapter are from a test version of NAVDAS. Other than the data assimilation, the model physics are the same as operational NOGAPS using MVOI. The name "NAVDAS" will be used to distinguish the new runs from operational NOGAPS, but these new runs still use the NOGAPS model.

A. 250 MB ISOTACH ANALYSIS

The 250 mb isotach MVOI analyses were deficient in the genesis stage of this cyclone, 24/00 and 24/12 (Fig. 5.9 and 5.10). Figures 6.1 and 6.2 show the NAVDAS 250 mb isotach analyses for 24/00 and 24/12, respectively. Improvements are seen for both the downstream and the upstream jet streaks with NAVDAS. Figure 6.1 shows the downstream jet streak has a longer and narrower jet core, which matches the sounding data better than the operational MVOI analysis (see Fig. 5.9). Additionally, the placement of the NAVDAS 110 kt and 120 kt isotachs matches the data better. In the upstream jet, improvements with NAVDAS include a more intense jet core, as well as an eastward extension of high wind speeds.

The 24/12 NAVDAS analysis also shows improvement compared to the operational MVOI analysis. While both analyses have the same intensity for the downstream jet streak, NAVDAS manages to place the 100 kt and 110 kt isotachs further

south, into North and South Carolina. While the analysis still shows some deficiencies, an improvement is noted. As with the 24/00 analysis, the upstream jet streak is stronger with NAVDAS, which better matches sounding data.

B. FORECAST TRACK POSITION

With improvement seen in the upper-level isotach analyses, forecast cyclone tracks were investigated next. Recall that the operational NOGAPS had a tendency to place the low too far east and to propagate it too fast. Figure 6.3 shows the forecast cyclone position from the 24/00 run of both operational NOGAPS and NAVDAS. The storm tracks are very similar for both runs, but the propagation speed for NAVDAS is slower than operational NOGAPS, which represents an improvement. However, the deepening rate of the low is insufficient with NAVDAS, as seen by the 10 mb discrepancy in the 36 h forecast (valid at 25/12).

Forecast tracks from the 24/12 run are seen in Fig. 6.4. NAVDAS forecasts show improvement in both position and speed over operational NOGAPS. The track is closer to the coast and NAVDAS is propagating the cyclone slower, which is closer to the truth. Again, note that NAVDAS does not deepen the storm as much as operational NOGAPS.

The 25/00 run also shows several improvements. The first is the 25/00 analysis position. Figure 6.5 shows that NAVDAS is to the northwest of the operational NOGAPS position. Recall that operational NOGAPS had an analysis position error to the southeast, so this shows an improved analyzed position with NAVDAS. It can then been seen that the NAVDAS forecast track is closer to the coast and the deepening rate is accurate. Overall, this 25/00 NAVDAS run shows significant improvement over operational NOGAPS.

C. 500 MB HEIGHT FORECASTS

It was seen in Chapter V that operational NOGAPS poorly forecast the 500 mb height fields. Mixed results are evident with 24 h forecasts from NAVDAS. Recall that a 500 mb cutoff forms and moves up the east coast from 25/00 to 25/12. Figure 6.6 shows both operational NOGAPS and NAVDAS produced poor 24 h forecasts from the 24/00 run (valid at 25/00). Neither develop the cutoff or build the downstream ridge adequately. In this example, NAVDAS was not able to show any improvement.

Figure 6.7 shows 24 h forecasts from the 24/12 run (valid at 25/12). Again, operational NOGAPS and NAVDAS both fail to forecast the 500 mb cutoff. However, some slight improvements can be seen with the NAVDAS forecast. First, although the cutoff is not forecast, NAVDAS does predict a narrower trough. In addition, some small improvements can be seen in the downstream curvature and the downstream ridge. So at 500 mb, an example of no improvement and one of slight improvement with NAVDAS are found.

D. PRECIPITATION FORECAST

Chapter IV showed that NOGAPS inability to forecast the precipitation associated with the baroclinic leaf at 24/12 resulted in a failure to forecast the heavy snow band at 25/12. Figure 6.8 shows the NAVDAS 12 h precipitation forecast from the 24/00 run (valid at 24/12). As with operational NOGAPS, the NAVDAS forecast also fails to predict the moderate to heavy precipitation through Georgia and the Florida panhandle. As a result, Fig. 6.9 shows the NAVDAS 36 h forecast (valid at 25/12) fails to predict the bent back feature and the associated heavy snow band. These results are similar to the

operational NOGAPS forecast (see Fig. 4.9), and no clear conclusion of improvement can be drawn.

In summary, the NOGAPS runs from NAVDAS do improve the forecast track of the cyclone. The NAVDAS runs unfortunately do not show improvement on other NOGAPS weaknesses such as the vigor of the mid-tropospheric development and precipitation forecasts.

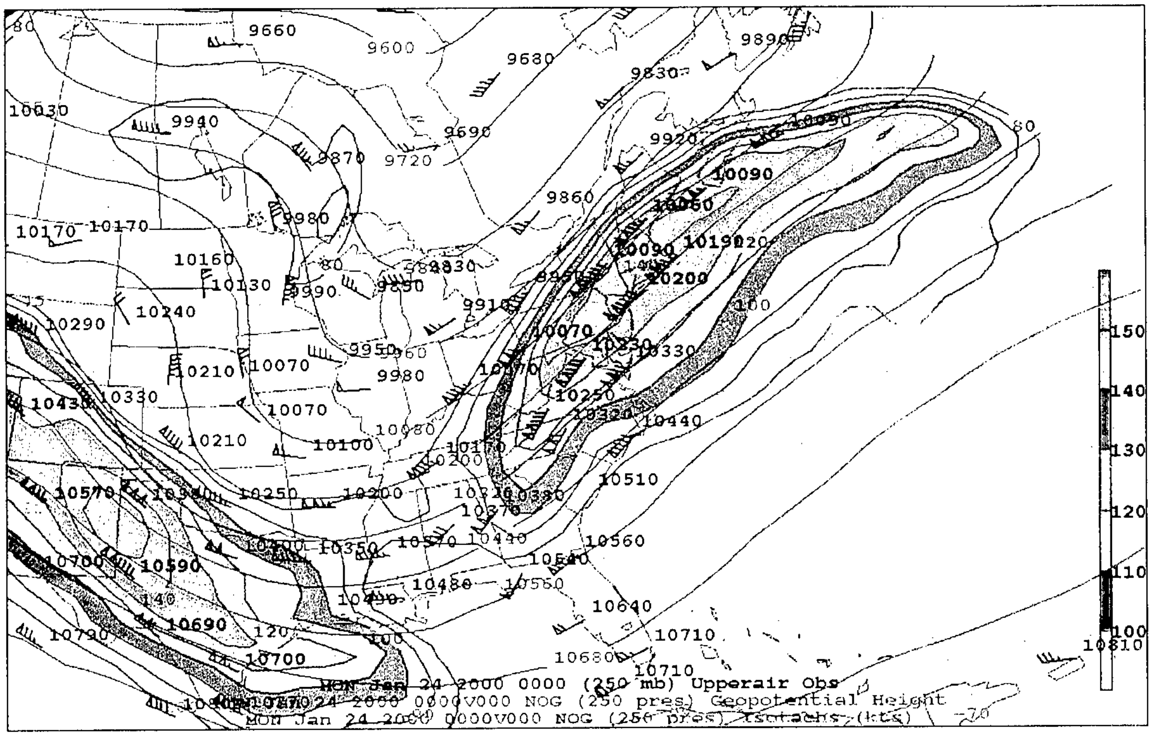


Figure 6.1. NAVDAS 250 mb Height and Isotachs from the 24/00 Analysis, with Sounding Data.

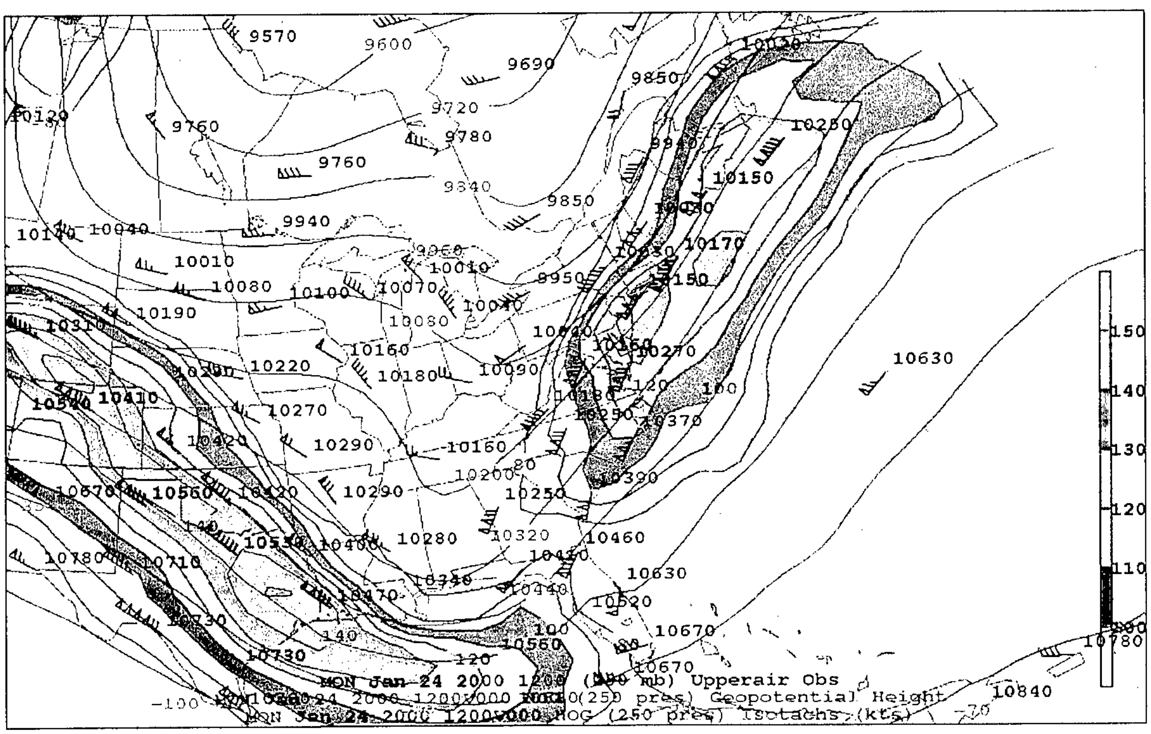


Figure 6.2. NAVDAS 250 mb Height and Isotachs from the 24/12 Analysis, with Sounding Data.

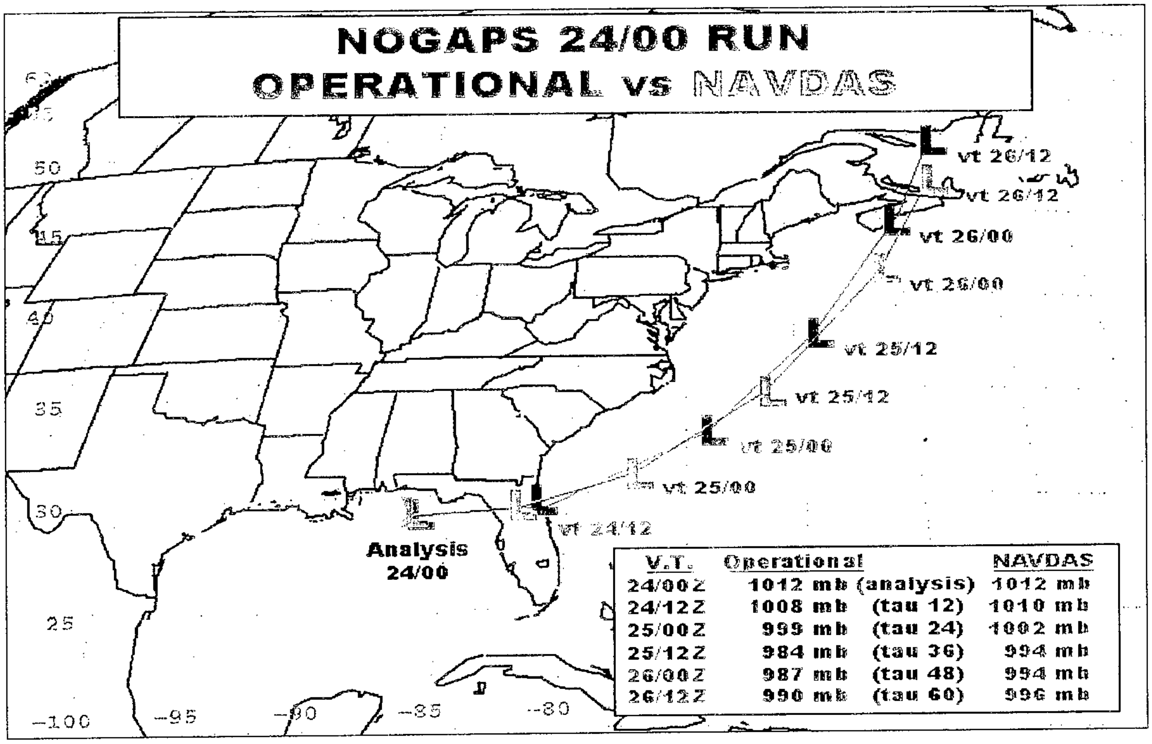


Figure 6.3. NAVDAS and Operational NOGAPS Forecast Cyclone Track from the 24/00 Run.

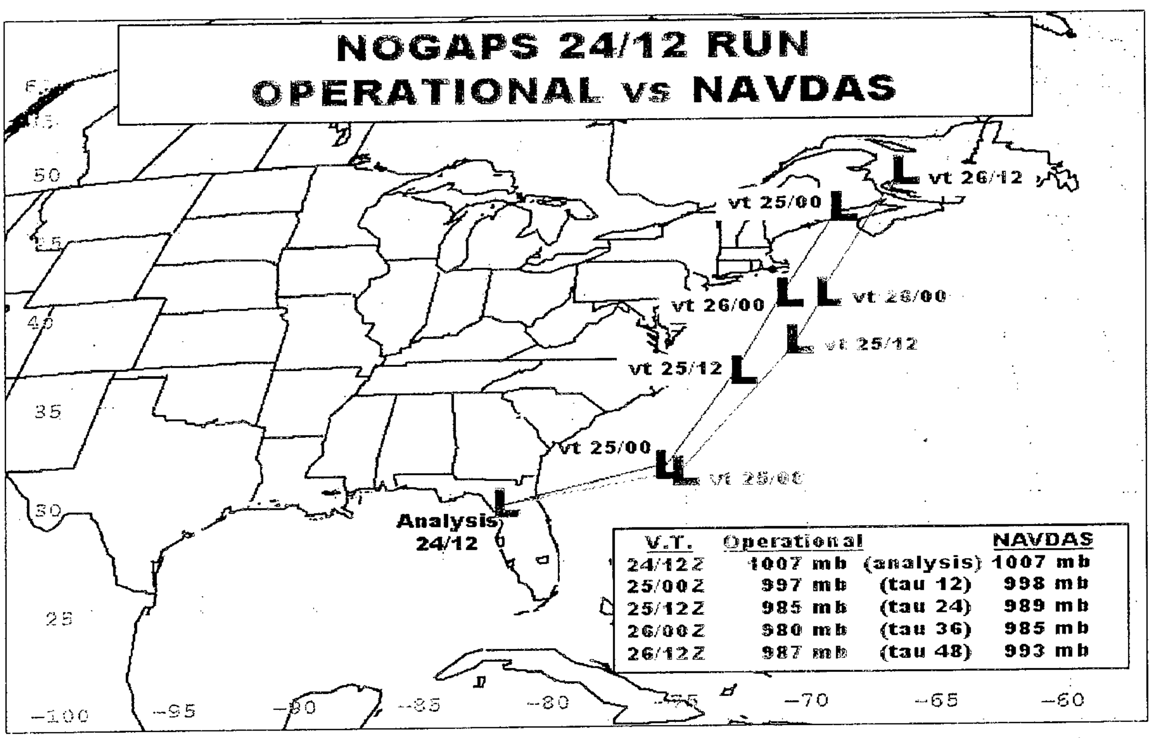


Figure 6.4. NAVDAS and Operational NOGAPS Forecast Cyclone Track from the 24/12 Run.

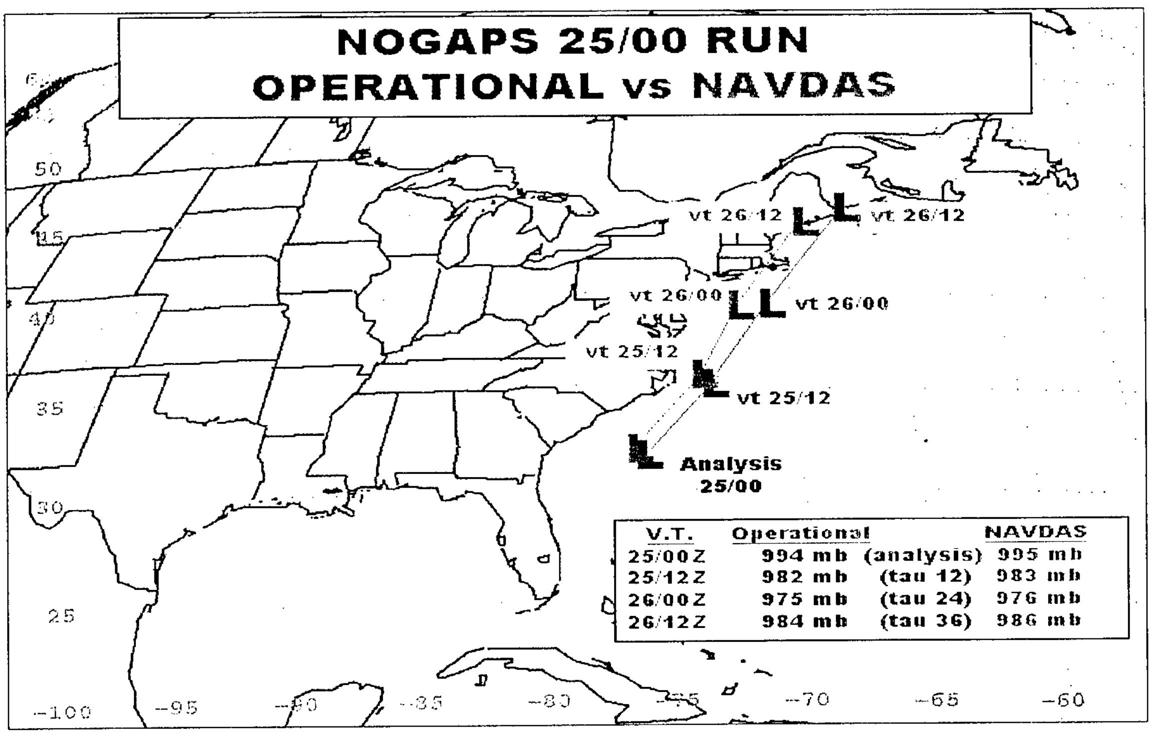


Figure 6.5. NAVDAS and Operational NOGAPS Forecast Cyclone Track from the 25/00 Run.

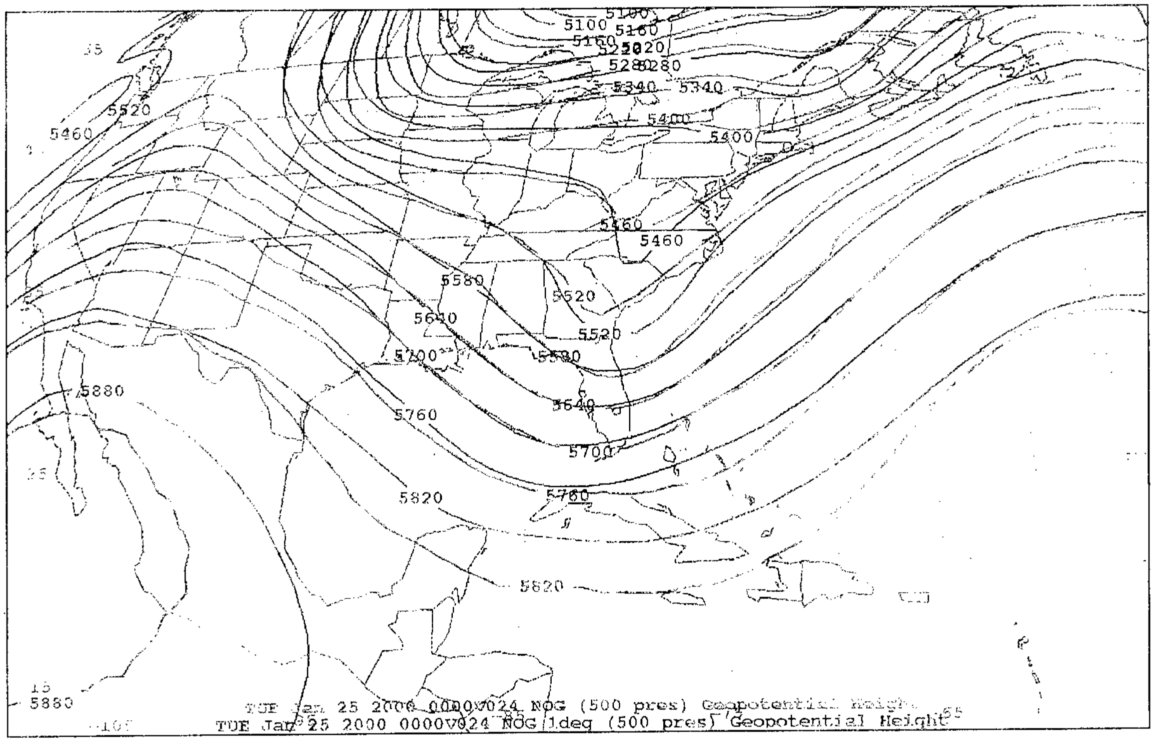


Figure 6.6. NAVDAS and Operational NOGAPS 24-Hour 500 mb Height Forecast from the 24/00 Run, Valid at 25/00.

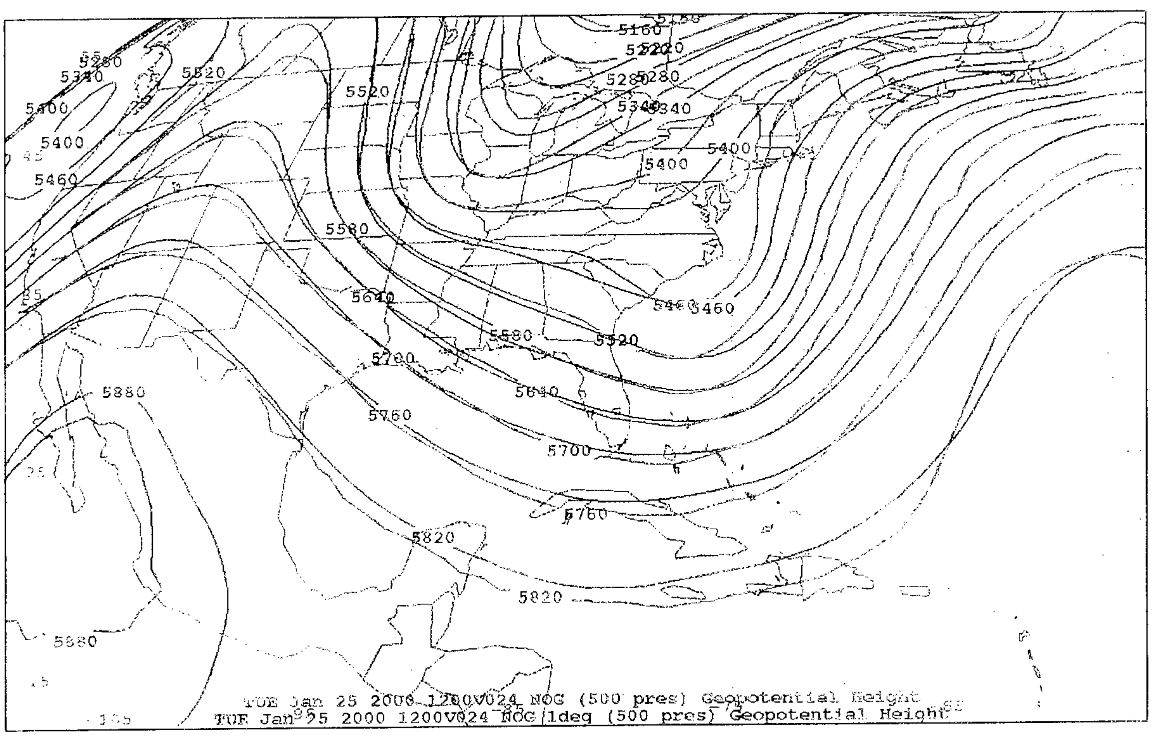


Figure 6.7. NAVDAS and Operational NOGAPS 24-Hour 500 mb Height Forecast from the 24/12 Run, Valid at 25/12.

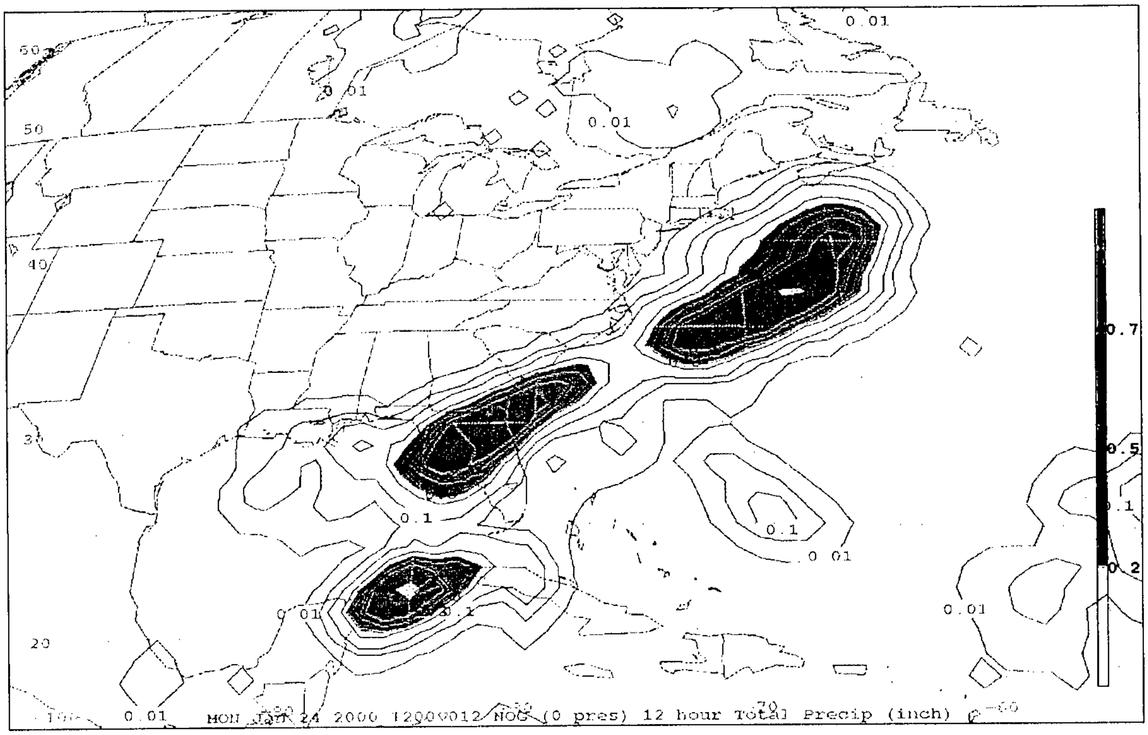


Figure 6.8. NAVDAS 12-Hour Precipitation Forecast from the 24/00 Run, Valid at 24/12.

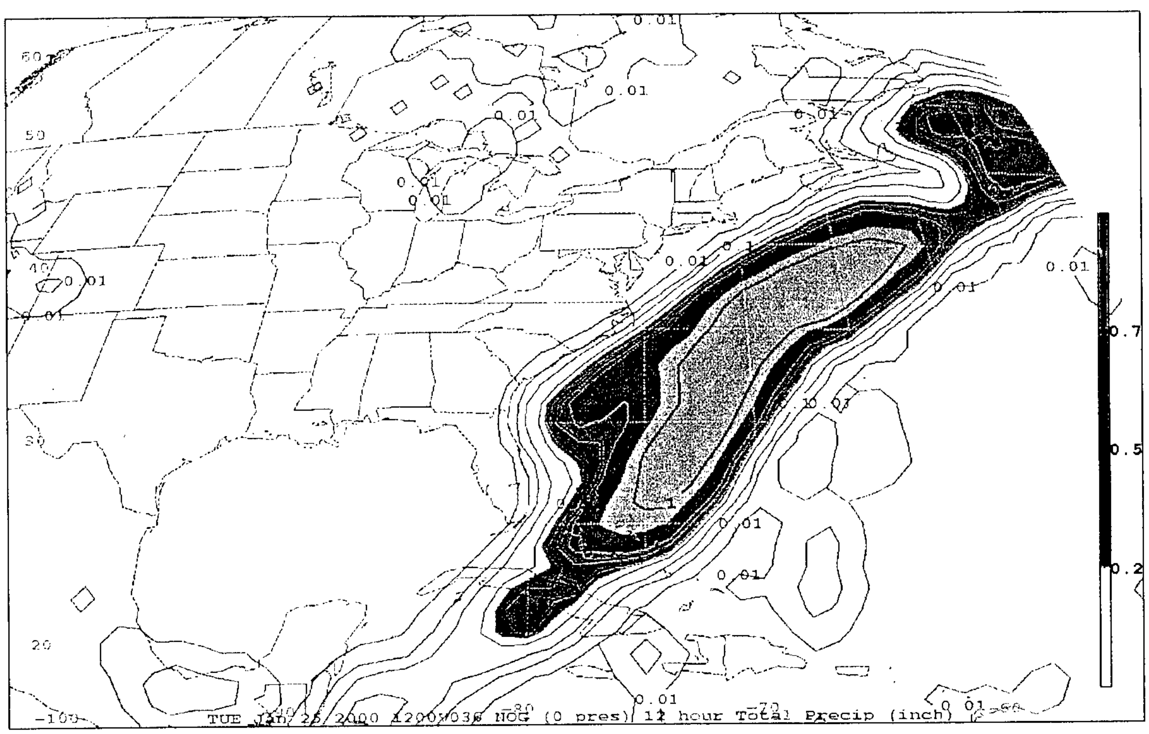


Figure 6.9. NAVDAS 36-Hour Precipitation Forecast from the 24/00 Run, Valid at 25/12.

THIS PAGE INTENTIONALLY LEFT BLANK

VII. CONCLUSION AND RECOMMENDATION FOR FURTHER STUDY

In this thesis, the 25 January 2000 East Coast cyclogenesis event and the performance of the Navy models, NOGAPS and COAMPS (West Atlantic), is investigated. Performance errors are observed, and several possible diagnoses for these errors proposed. To determine details of this interesting case of cyclogenesis, data from several sources were used. A general synoptic picture was drawn using the NOGAPS analysis fields. Once this was established, observational data were used to validate the analyses and forecasts. These data included: IR imagery, water vapor imagery, radar composites, sounding data, surface observations, airport hourly reports, ship reports, and buoy data.

Positional errors were evident in the NOGAPS analysis. In contrast, the COAMPS analyses were very good and described the storm track well. NOGAPS analyses, especially for 25/00 and 25/12, misplace the storm to the southeast of the true position. Such errors were readily apparent in the short range forecast positions for these times as well. While COAMPS performs better, it was not perfect by any means. Early runs from both models place the storm too far east and propagate it too fast. The errors are more severe with NOGAPS.

With the use of upper-level sounding data, the difficulty of both models in developing a strong trough/ridge system is revealed. Short range forecasts handle the upper-level development poorly, which led to poor storm position forecasts. Just as significant is the inability of the models to accurately analyze and forecast two strong jet

streaks at 250 mb. Soundings reveal a pronounced acceleration zone into a jet streak aligned with the US East Coast. Both NOGAPS and COAMPS have difficulty capturing this feature in their analysis. In turn, the upper-level wind forecasts fail to predict the intensity of this jet streak feature. This problem, in addition to height field inaccuracies, creates deficiencies in the upper-level divergence pattern which directly influences the development of the surface cyclone.

The height field errors were most likely affected by latent heat release. This finding is implied from the forecast precipitation. As was seen in IR imagery, a baroclinic leaf over Georgia and Florida at 24/12 had moderate to heavy precipitation associated with it. Through 25/00 and 25/12 a bent back feature developed that very closely correlated with the heavy snow band. Both models' 24/00 run failed to predict the heavy precipitation associated with the baroclinic leaf. Both models show poor precipitation forecasts for 25/00 and 25/12 and fail to forecast the bent back feature. The NOGAPS 24/12 run had similar results. However, the 12 h forecast from the COAMPS 24/12 run did partially resolve the precipitation from the baroclinic leaf, and the bent back feature is in the 24 h forecast. There are positional errors, but the features are resolved. The inability to handle this baroclinic leaf, and its associated moisture, led to poor short range precipitation forecasts and upper-level height forecasts.

A manual analysis of surface temperatures reveals a strong coastal front along the Carolina coast preceding the cyclogenesis. The high horizontal resolution of COAMPS resolves the low-level coastal front, while it is not captured well by NOGAPS. This impacts NOGAPS ability to analyze and forecast the strength of the low-level baroclinic zone. COAMPS is able to analyze, and to a certain extent, forecast the low-level

baroclinic zone. The better storm track with COAMPS is influenced by the model's ability to capture the coastal front.

Results from the NAVDAS forecast runs are encouraging. Improvements in the forecast track and 250 mb isotach analyses are evident. Unfortunately little or no improvements are observed in the precipitation and 500 mb height forecasts for this case.

Areas of future study must involve NAVDAS. More comparisons of NAVDAS with operational MVOI need to be completed. While this variational data assimilation scheme will not make a global model perfect, it certainly can improve it. One example is the sounding data. With NAVDAS ingesting data from mandatory and significant levels, not just the mandatory levels as with MVOI, more small scale structure will be resolved. A global model will always have difficulty resolving mesoscale features such as cold air damming and coastal fronts until computational power allows the horizontal resolution to increase.

The 24-25 January 2000 cyclone shows that forecasting East Coast cyclones remains a challenge. The diagnosis of cases like this one document the current skill of today's Navy models and illustrates analysis and prediction problems yet to be solved.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX. ADDITIONAL ANALYSES AND DATA

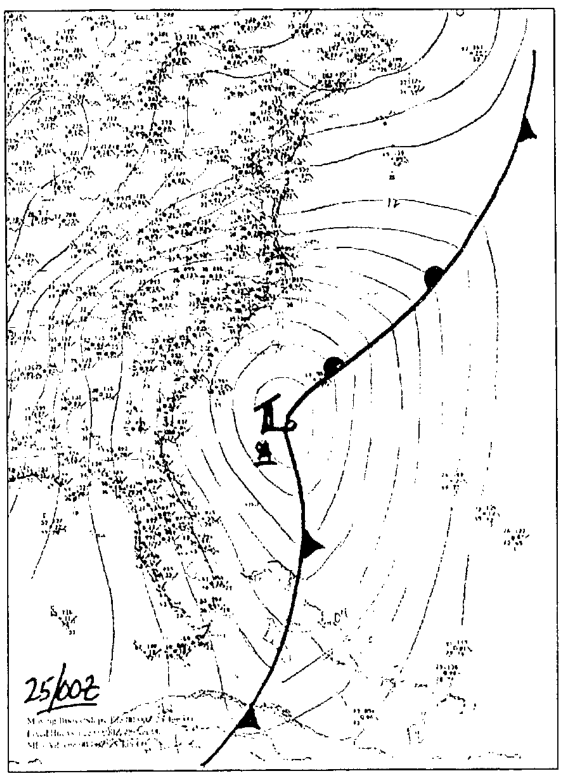


Figure A1. NWS 25/00 Manual Analysis. (from: LaCorte, 2000)

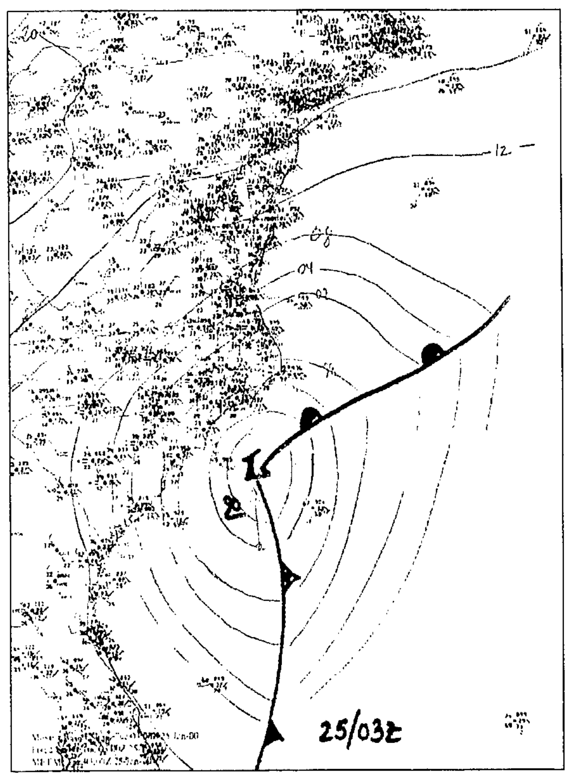


Figure A2. NWS 25/03 Manual Analysis. (from: LaCorte, 2000)

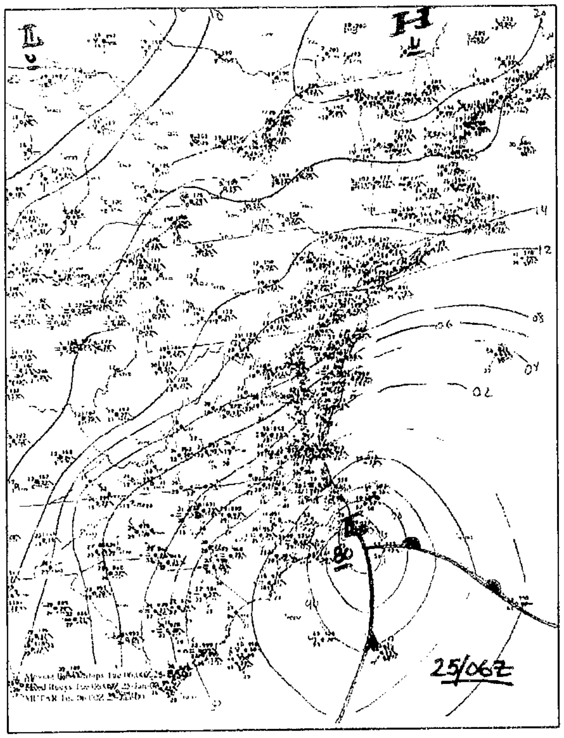


Figure A3. NWS 25/06 Manual Analysis. (from: LaCorte, 2000)

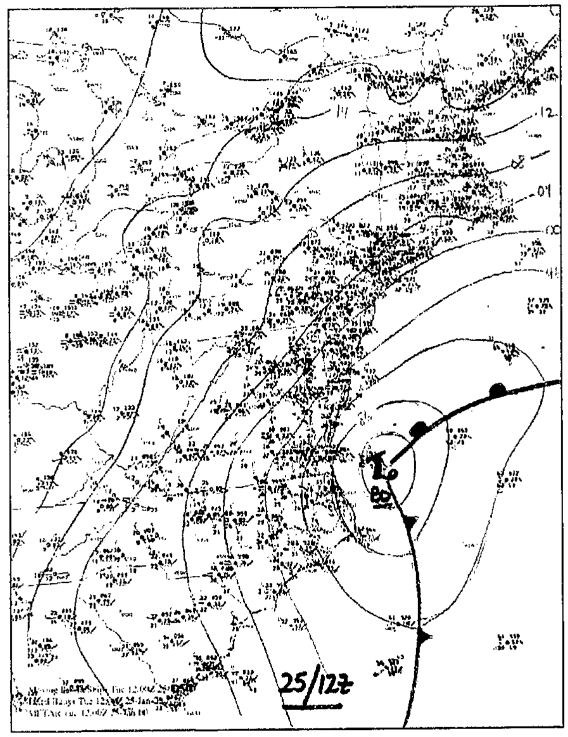


Figure A4. NWS 25/12 Manual Analysis. (from: LaCorte, 2000)

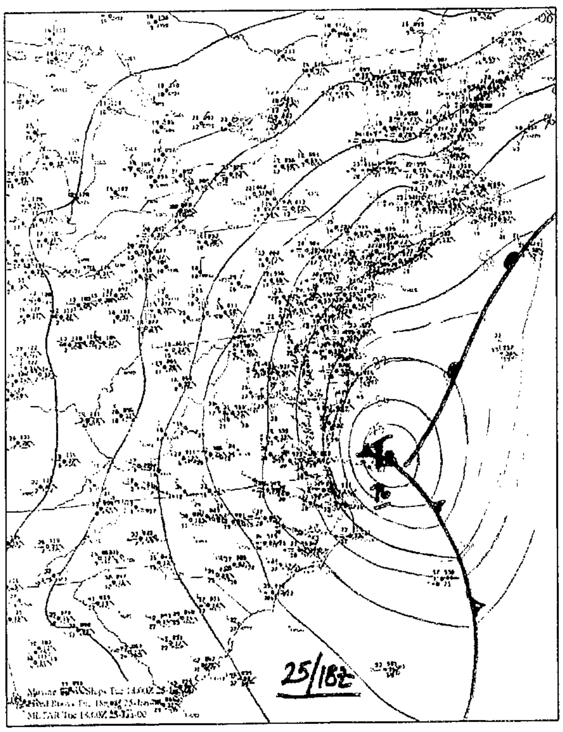


Figure A5. NWS 25/18 Manual Analysis. (from: LaCorte, 2000)

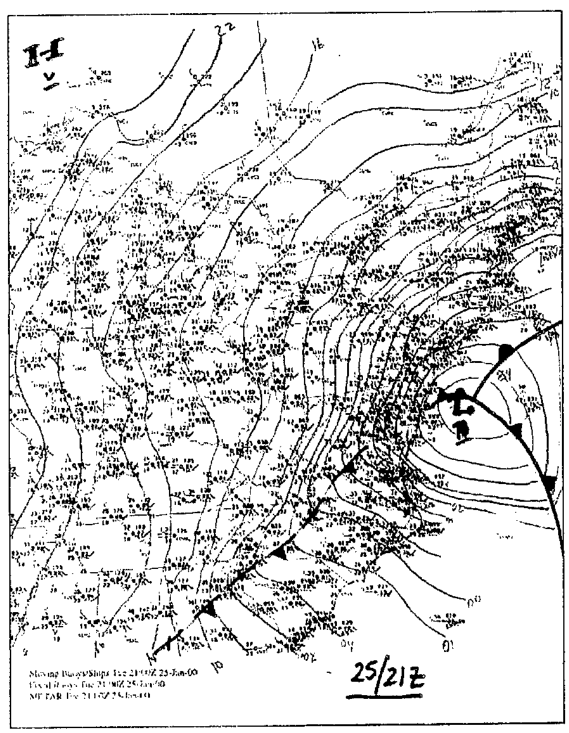


Figure A6. NWS 25/21 Manual Analysis. (from: LaCorte, 2000)

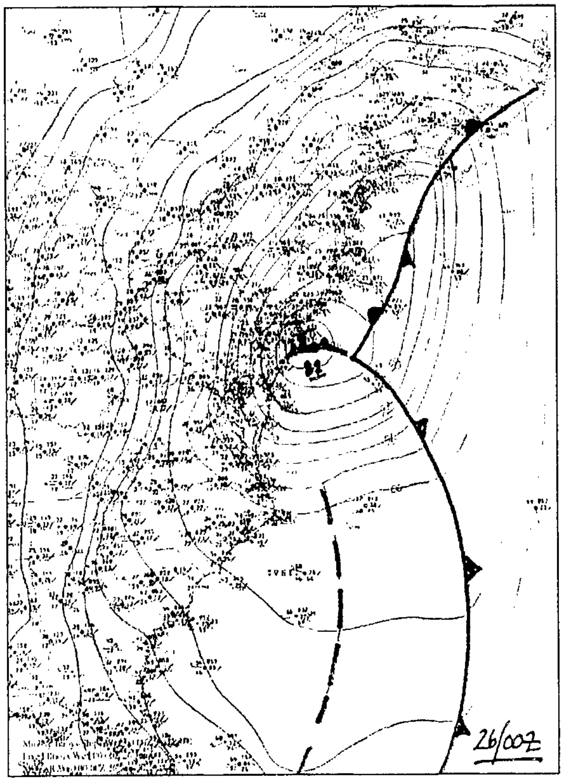


Figure A7. NWS 26/00 Manual Analysis. (from: LaCorte, 2000)

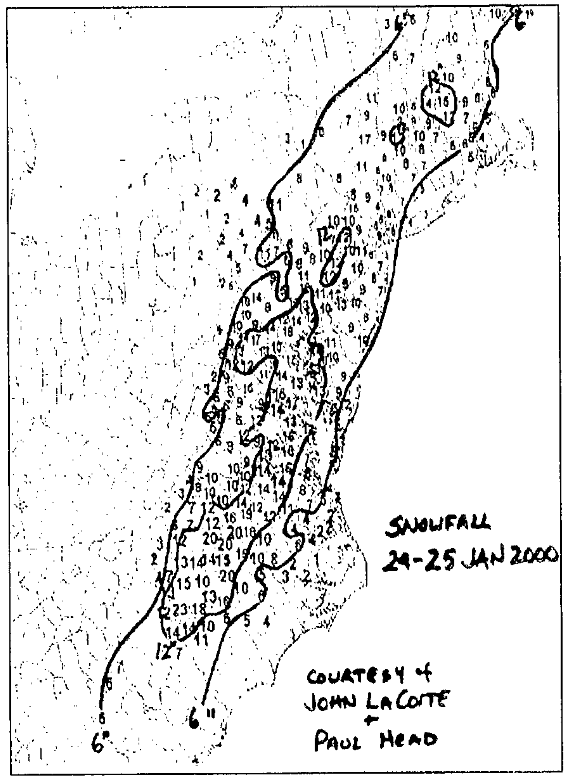


Figure A8. NWS Manual Snowfall Analysis. (from: LaCorte, 2000)

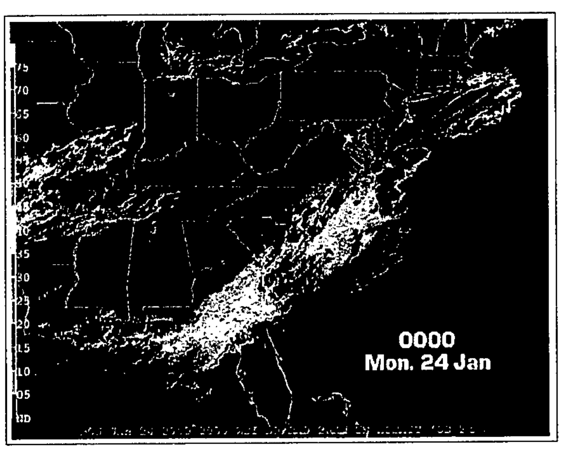


Figure A9. Radar Mosaic for 24/00. (from: COMET, 2000)

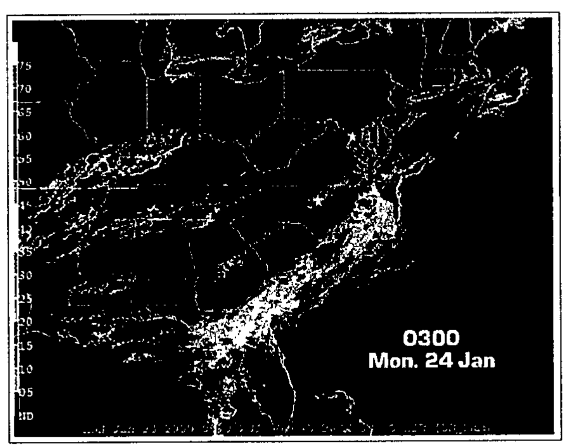


Figure A10. Radar Mosaic for 24/03. (from: COMET, 2000)

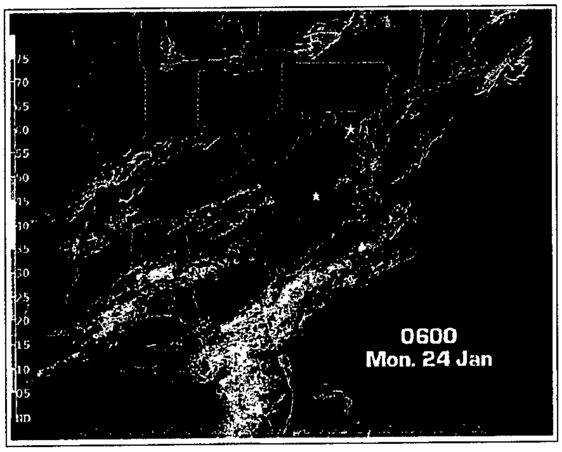


Figure A11. Radar Mosaic for 24/06.
(from: COMET, 2000)

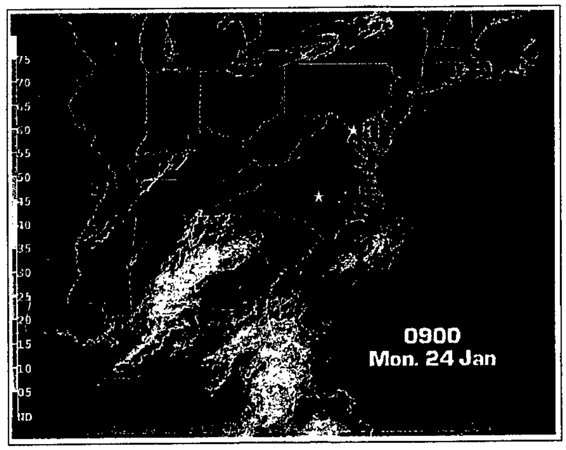


Figure A12. Radar Mosaic for 24/09.
(from: COMET, 2000)

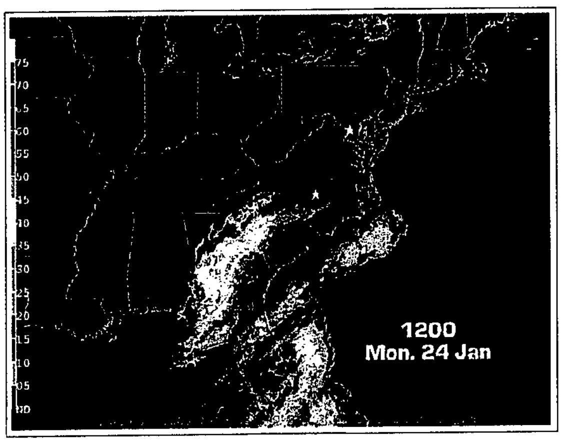


Figure A13. Radar Mosaic for 24/12.
(from: COMET, 2000)

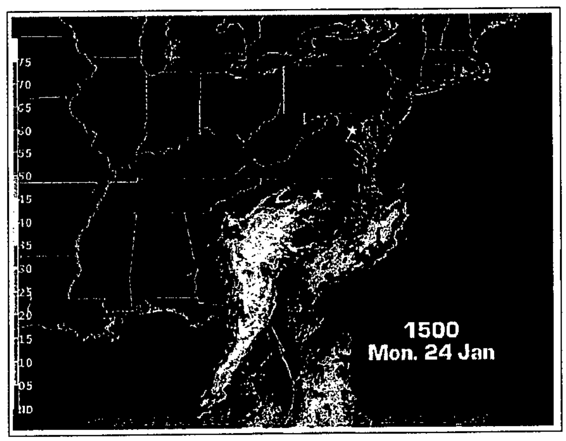


Figure A14. Radar Mosaic for 24/15.
(from: COMET, 2000)

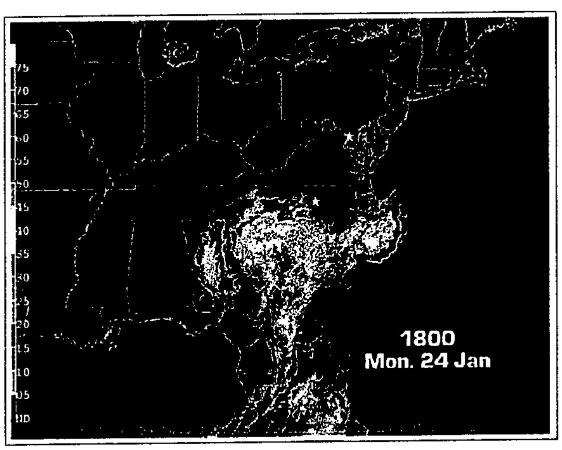


Figure A15. Radar Mosaic for 24/18.
(from: COMET, 2000)

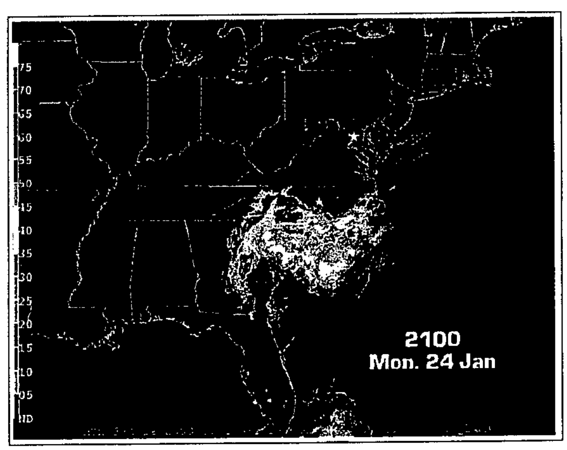


Figure A16. Radar Mosaic for 24/21.
(from: COMET, 2000)

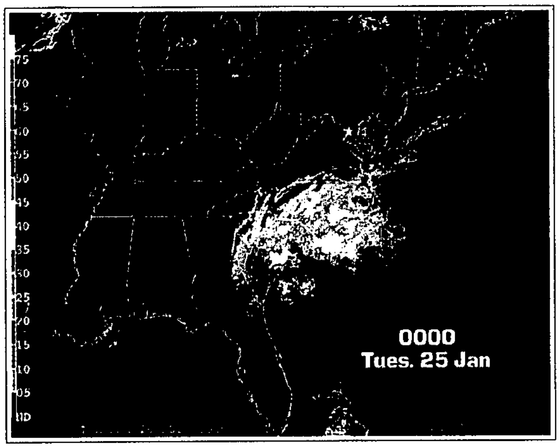


Figure A17. Radar Mosaic for 25/00.
(from: COMET, 2000)

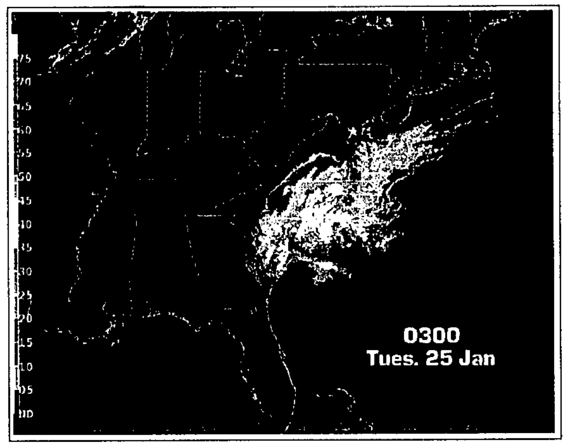


Figure A18. Radar Mosaic for 25/03.
(from: COMET, 2000)

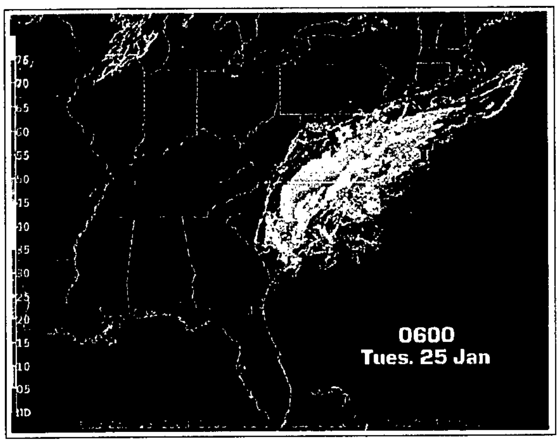


Figure A19. Radar Mosaic for 25/06.
(from: COMET, 2000)

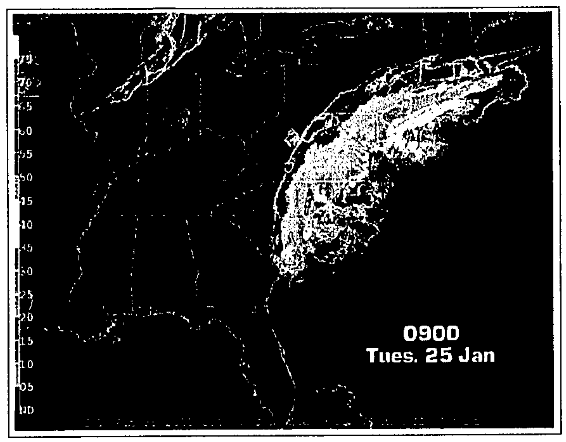


Figure A20. Radar Mosaic for 25/09.
(from: COMET, 2000)

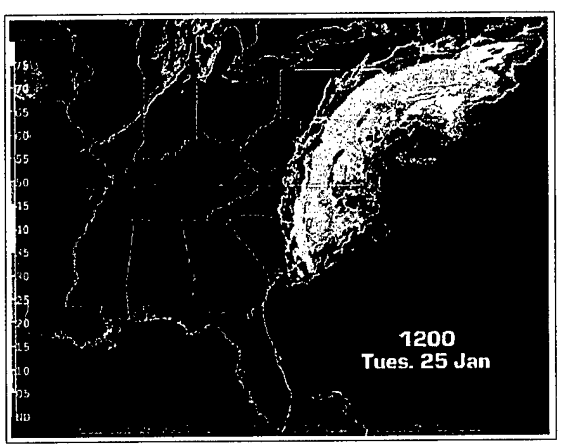


Figure A21. Radar Mosaic for 25/12.
(from: COMET, 2000)

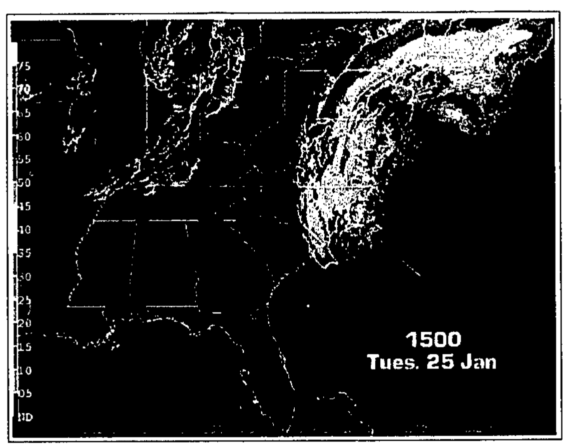


Figure A22. Radar Mosaic for 25/15.
(from: COMET, 2000)

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

Ahrens, C. Donald, *Meteorology Today: An Introduction to Weather, Climate, and the Environment*, 4th ed., West, 1991.

Barker, E.H., "Design of the Navy's Multivariate Optimum Interpolation Analysis System," *Weather and Forecasting*, 7(2), pp. 220-231, 1992.

Bayler, G., et al., "The Navy Operational Global and Regional Atmospheric Prediction Systems at the Fleet Numerical Oceanography Center," *Weather and Forecasting*, 7(2), pp. 273-279, 1992.

Bell, G.D. and Bosart, L.F., "Appalachian Cold-Air Damming," *Monthly Weather Review*, 116, pp. 137-161, 1988.

Bosart, L.F., "New England Coastal Frontogenesis," *Quart. J. Roy. Meteor. Soc.*, 101, pp. 957-978, 1975.

Carlson, Toby N., *Mid-Latitude Weather Systems*, Harper Collins Academic, 1991.

Cooperative Program for Operational Meteorology, Education and Training (COMET), "Case Support Materials for UCAR/COMET and NWS/OM Case Study 24: 25 January 2000."
[http://www.comet.ucar.edu/resources/cases/c24_25jan2000/index.htm]. 2000.

Daley, R. and Barker, E.H., *NAVDAS Source Book 2000: NRL Atmospheric Variational Data Assimilation System*, NRL Publication NRL/PU/7530--00-418 (153 pp.), 2000.

Forbes, G.S., Anthes, R.A., and Thompson, D.W., "Synoptic and Mesoscale Aspects of an Appalachian Ice Storm Associated with Cold-Air Damming," *Monthly Weather Review*, 115, pp. 564-591, 1987.

Hodur, R.M., "The Naval Research Laboratory's Coupled Ocean/Atmosphere Mesoscale Prediction System," *Monthly Weather Review*, 125(7), pp. 1414-1430, 1997.

Kocin, Paul J. and Uccellini, Louis W., *Snowstorms Along the Northeastern Coast of the United States: 1955 to 1985*, American Meteorological Society, 1990.

LaCorte, John, "The 'No-Surprise' Snow Storm of 24-25 January 2000."
[http://bookend.met.psu.edu/~lacorte/25jan2000/25jan2000.html]. 2000.

National Centers for Environmental Prediction, "EMC Model Guidance for the Blizzard of 2000."
[http://www.emc.ncep.noaa.gov/mmb/research/blizz2000]. 2000.

National Data Buoy Center.
[http://www.ndbc.noaa.gov]. Jan 2001.

Shapiro, M.A. and Keyser, Daniel, "Fronts, Jet Streams and the Tropopause," *Extratropical Cyclones: The Erik Palmen Memorial Volume*, pp. 167-191, American Meteorological Society, 1990.

Uccellini, Louis W., "Processes Contributing to the Rapid Development of Extratropical Cyclones," *Extratropical Cyclones: The Erik Palmen Memorial Volume*, pp. 81-105, American Meteorological Society, 1990.

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center 2
   8725 John J. Kingman Road, Suite 0944
   Ft. Belvoir, VA 22060-6218

2. Dudley Knox Library 2
   Naval Postgraduate School
   411 Dyer Road
   Monterey, CA 93943-5101

3. Oceanographer of the Navy (N096T) 1
   US Naval Observatory
   3450 Massachusetts Ave., NW
   Washington, DC 20392-5421

4. Fleet Numerical Meteorology and Oceanography Center 1
   7 Grace Hopper Ave., Stop 1
   Monterey, CA 93943-5501

5. Dr. Carlyle H. Wash 5
   Naval Postgraduate School, Meteorology Department, Code MR
   589 Dyer Road Root Hall
   Monterey, CA 93943-5114

6. Dr. Patricia M. Pauley 1
   NRL, Monterey
   7 Grace Hopper Ave., Stop 2
   Monterey, CA 93943-5501

7. Mr. Bob Creasey 1
   Naval Postgraduate School, Meteorology Department, Code MR
   589 Dyer Road Root Hall
   Monterey, CA 93943-5114

8. LCDR Gregory J. Schmeiser, USN 1
   1913 Somersby Ln
   Virginia Beach, VA 23456